Sciences of Europe

No 189 (2026)

Sciences of Europe
(Praha, Czech Republic)

ISSN 3162-2364
The journal is registered and published in Czech Republic.
Articles in all spheres of sciences are published in the journal.

Journal is published in Czech, English, Polish, Russian, Chinese, German and French, Ukrainian.
Articles are accepted each month.
Frequency: 24 issues per year.
Format - A4
All articles are reviewed
Free access to the electronic version of journal

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E-mail: info@european-science.org
Web: www.european-science.org

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ART STUDIES

THE KAZAKH DOMBRA *KÜY* AS A FORM OF ARTISTIC EXPRESSION (BASED ON THE WORKS OF KURMANGAZY AND DAULETKEREY)

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DOI: 10.5281/zenodo.20456814

ABSTRACT

This article examines the Kazakh dombra *küy* as a form of realization of individual musical thinking in the works of 19th-century traditional musicians – Kurmangazy Sagyrbayuly and Dauletkerey Shygaiuly. Proceeding from the understanding of the *küy* as a processual form that emerges in the act of performance, the study identifies differences in the types of musical thinking of Kurmangazy and Dauletkerey. These differences manifest at all levels of musical organization – from the interpretation of stable structural models of the *küy* and principles of temporal development of thematic material to performance plasticity and articulation techniques. It is argued that Kurmangazy's *küys* embody a directed, energetically impulsive type of musical thinking, whereas Dauletkerey's *küys* reflect a more introspective mode, oriented toward inner experience and intonational concentration.

This approach allows the *küy* to be considered as a mode of sonic modeling of different ways of experiencing and interpreting reality within traditional culture, and opens up new perspectives for further research within the frameworks of musical thinking theory and cultural anthropology.

Keywords: Kazakh traditional music, *küy*, dombra, musical thinking, Kurmangazy, Dauletkerey, segmental (buyn-based) form, intonation, musical time, performance plasticity.

Introduction

The Kazakh dombra tradition constitutes one of the principal forms of national musical culture, within which stable models of artistic expression are crystallized and realized through the genre of the instrumental piece known as the *kui*–a traditional solo composition for the dombra. Within Kazakh musicological scholarship, the dombra tradition is conceptualized as a significant repository of the historical and cultural memory and artistic experience of the Kazakh people [1, p. 5; 2, p. 22; 3, p. 55].

In this tradition, the *kui* does not exist as an autonomous or fixed musical text. Rather, it emerges in the process of performance, remaining inseparable from the embodied gesture of the *kuyshi* – the traditional musician who functions simultaneously as performer and creator – and is not codified in a definitive written form. This ontological status allows the *kui* to be understood not as a completed composition, but as a fluid and processual form in which meaning is generated through temporal sonic unfolding [4, p. 78].

Within this framework, it becomes evident that even within a single regional school–despite the presence of relatively stable performance conventions and recurring structural models–no singular approach to the realization of the *kui* exists. This plurality is embedded within the tradition itself, which sustains the notion that "each *kuyshi* performs their own character" [5, p. 69]. Individuality thus manifests not only at the level of stylistic variation, but also at deeper levels of musical organization, reflecting distinct modes of musical thinking. These modes may be understood as particular systems of intonational cognition and the structuring of sonic experience [6, p. 159].

In this regard, the works of the canonical figures of Kazakh dombra music–Kurmangazy Sagyrbayuly (1823–1897) and Dauletkerei Shygaiuly (1820–1887)–are especially illustrative. Their творчество exemplifies two distinct approaches to the organization of musical expression within the 19th-century Kazakh dombra tradition. While belonging to the same regional performance school and the same stylistic phase of the *tokpe* instrumental tradition, their compositions reveal markedly different modes of artistic thinking. These differences are particularly evident in their respective approaches to temporal development and the unfolding of the *kui* [1, p. 59; 7, p. 210].

Features of the Organization of Musical Thinking in the *Kui*s of Kurmangazy

Kurmangazy Sagyrbayuly stands as one of the most prominent representatives of the Kazakh dombra tradition, whose творчество occupies a central position in the formation of the Western Kazakh *tokpe* school. His *kui*s–such as *Saryarka*, *Adai*, and *Balbyraun*–have attained the status of canonical works within traditional instrumental art and serve as key representations of his artistic system.

Within this system, the *kui* unfolds as a form of directed sonic action grounded in the principle of energetic development of musical material. Despite the autobiographical origins of many of his works, these compositions do not merely depict reality; rather, they enact its sonic interpretation. Musical unfolding organizes both sonic space and time, generating a strongly directional trajectory of development.

Importantly, "energy" in this context cannot be reduced to tempo, dynamics, or motor activity alone; instead, it functions as a deeper manifestation of the *kuyshi*'s musical thinking. This is particularly evident in Kurmangazy's treatment of the *buyn*-based structural model characteristic of the Western Kazakh tradition, organized through the succession of register zones (*bas buyn – orta buyn – saga*). In his works, this structure operates as a model of linear energetic unfolding: *bas buyn* represents the zone of initial concentration, *orta*

buyn the phase of impulse development, and *saga* the culmination point of maximum tension. This compositional logic corresponds to established studies on the structure of the dombra *kui* and traditional compositional terminology [8, p. 49; 1, p. 25; 12, p.156].

Such a dramaturgical trajectory is particularly evident in the *kui Adai*, where register expansion is experienced as sonic expansion and spatial amplitude. The освоение of a new register acquires the status of a semantic coordinate of form: upward movement correlates with an increase in intensity, while the culminating zone functions as the energetic center of the composition. The expansion of the culminating space–characteristic of several of Kurmangazy's *kui*s, including the introduction of a second *saga*–reflects the composer-performer's fundamental orientation toward prolonging and intensifying the energetic impulse.

A similar logic governs thematic development, where repetition does not stabilize the material but instead accumulates tension, preparing further movement. Musical time is structured as a process of continuous internal dynamism, in which even post-climactic sections are perceived not as closure, but as forms of energetic release. This is particularly evident in *Saryarka*, where the combination of *buyn*-based and transpositional logic results in a sequential descent following the climax that does not diminish tension but transforms it into a different energetic state.

The powerful energetic quality of Kurmangazy's musical process is also directly expressed in his distinctive articulation techniques. The stroke pattern *kara kagys*, characteristic of the Western Kazakh tradition, with its bidirectional (upward and downward) motion, generates a specific type of sonic motoricity in which each stroke functions as an impulse. The performative gesture here not only produces sound but structures musical time, segmenting it into a sequence of intentional acts. As a result, sound is perceived not as a neutral acoustic outcome, but as the manifestation of directed externalized force. This aligns with the broader logic of musical development in Kurmangazy's *kui*s, which is grounded in impulse, tension, and overcoming. Such an interrelation between performative gesture, sonic motoricity, and the cultural function of the instrument corresponds with approaches that interpret folk instrumental music as an integrated cultural phenomenon [9, p. 54; 10, p. 99].

It is also significant that within cultural memory, Kurmangazy is represented as a historical figure of strong volitional and active character, which correlates with the identified type of musical thinking. His *kui*s are perceived as forms of active engagement with the world–as artistic spaces of action, resistance, and energetic assertion. In this context, the dombra emerges as an instrument of cultural will, and musical expression as a mode of sonic interpretation of lived experience.

Thus, within Kurmangazy's artistic system, energy functions not as a secondary stylistic feature, but as a fundamental principle organizing musical time, form, and meaning, ultimately defining the very nature of his sonic thinking.

Features of the Organization of Musical Thinking in the *Kui*s of Dauletkerei

In contrast to Kurmangazy, the artistic world of Dauletkerei represents a reflective type of musical thinking, in which the dramaturgy of action is supplanted by a logic of inner experience. Intonational unfolding loses its impulsive, directional character and acquires a quality of inward concentration. In this context, the dombra functions as a space of intonational reflection, where musical expression develops as an internal monologue.

Dauletkerei's mode of artistic thinking is closely linked to his social and cultural background: his affiliation with an aristocratic milieu, combined with a high level of education and refined aesthetic sensibility, shaped a model of artistic consciousness oriented not toward action, but toward contemplation and the internal formation of meaning. His artistic world is associated with a lyrical mode of perception, characterized by softness of intonation, plasticity of sonic movement, and subtle emotional nuance [10, p. 59]. Within the tradition, this is aligned with the concept of *nəziktik*–denoting inward focus and psychological delicacy. It is therefore not coincidental that a significant portion of Dauletkerei's oeuvre engages with feminine imagery, in which the dombra functions not as a vehicle of volitional expression, but as a medium of intonational intimacy.

Musical development in Dauletkerei's *kui*s lacks impulsive directionality and is perceived as a process of deepening. Intonation is not oriented toward action, but evolves through variation and refinement, repeatedly returning to foundational intonational models. Meaning is generated not through climactic rupture, but through subtle shifts in sonic articulation. Within this framework, the traditional *buyn* structure is preserved as an external framework, while developmental processes are displaced into the internal plane–manifested in micro-intonational shifts and variant deviations. Repetition thus functions not as a means of stabilization, but as a mechanism of intensification and deepening. In *kui*s such as *Zhiger*, *Topan*, and *Salyk Olgen*, each thematic return is perceived as a new intonational state.

At the same time, the освоение of new register zones occurs gradually, through a chain of intermediate states. The culmination (*saga*) loses the character of a sharp structural rupture and instead emerges as the result of internal concentration, growing organically out of the preceding material rather than opposing it. In *Zhiger*–one of the composer's most philosophically profound works–tension is achieved not through contrast, but through the gradual densification of the intonational texture.

Such a developmental logic gives rise to a distinctive form of musical time, which loses its linear directionality and assumes the character of enclosed inward movement. Motion unfolds not forward, but inward. Register-based dramaturgy is likewise governed by the principle of gradual saturation: a tendency toward middle registers and the avoidance of the highest tessitura (*ulken saga*) generate a sense of balance and depth.

A comparable logic is evident in performance practice. Dauletkerei's characteristic manner of play-

ing, associated with the aesthetic of *tore kagys* (aristocratic restraint, softness, and nobility of gesture), is realized through specific technical means, notably the stroke technique *ilme kagys*, which produces a refined and intonationally differentiated sound. As a result, sound is not asserted, but emerges as the outcome of a fluid intonational gesture. Musical time loses its impulsive segmentation and is experienced as continuous flow. In this context, articulation functions not merely as a technical parameter, but as an embodied form of musical thinking.

Thus, within Dauletkerei's artistic system, movement is transformed into reflection, energy into inner concentration, and form into a process of gradual emergence of meaning. Music appears as a space of intonational self-reflection and a distinctive mode of sonic engagement with the world.

The *Kui* as a Form of Artistic Thinking: A Comparative Analysis

The analysis undertaken allows the works of Kurmangazy and Dauletkerei to be interpreted as manifestations of two distinct models of musical thinking, each operating differently with musical intonation, the organization of sonic time, and formal structure. These differences extend to the deeper mechanisms of meaning formation and enable the dombra tradition to be understood as a space in which multiple modes of cultural interpretation and signification coexist.

These distinctions are most clearly articulated in the treatment of musical form. Within the energetic model (Kurmangazy), form assumes the character of directed architecture. The composition is constructed as a dynamic structure oriented toward the attainment of a climax, while register movement functions as an equivalent of dramaturgical action.

In contrast, within the reflective model (Dauletkerei), form loses the rigidity of architectural construction and is instead perceived as a process. While the external structural scheme is preserved, the center of development shifts inward, into the domain of variant transformation, where repetition operates as a means of semantic deepening rather than structural reinforcement.

The spiral compositional logic characteristic of the *buyn*-based *tokpe kui* is realized differently within these two models. In the energetic model, it is directed toward the climax; in the reflective model, it is associated with return and inward intensification.

Musical time is likewise organized differently. In the energetic model, it assumes a vectorial character, oriented toward forward motion and the accumulation of tension. In the reflective model, time is experienced as duration and inward unfolding, where repetition stabilizes a state rather than leading toward release. In this sense, the dombra *kui* embodies distinct cultural models of temporality–time as action and time as contemplation.

Differences are also evident in thematic organization. In Kurmangazy's works, development unfolds as a structured progression with clear functional differentiation of material. In contrast, Dauletkerei's thematic process is based on variant fluidity, blurring the boundaries between developmental phases. Here, development occurs through internal transformation rather than directed dramaturgical progression.

Register functions differently in each model as well. In the energetic model, it provides the structural framework of the composition and actively participates in the formation of the climax. In the reflective model, its structural role is diminished, and it becomes integrated into the process of gradual intonational deepening.

At the core of these differences lies the differing status of intonation. In the energetic model, intonation operates as an impulse that organizes formal movement. In the reflective model, it acquires the character of inner speech, where development is achieved through subtle variant shifts. These distinctions are not merely stylistic, but indicative of fundamentally different types of musical thinking that determine modes of sonic experience. From this perspective, intonation functions as a form of musical thought in becoming, shaping the processual nature of form [11, p. 46].

It is significant that within the Kazakh tradition, the *kui* is understood as a form of direct engagement with reality. Musical expression emerges as a response, evaluation, or articulation of an internal state, while the dombra serves as a mediator of cultural experience. In one case, this is realized as active sonic action; in the other, as a form of intonational self-reflection.

Approached from this perspective, the dombra tradition extends beyond the boundaries of purely musical form and can be interpreted as a cultural practice in which sound, behavior, and cognition form an integrated system [13, p. 259; 14, p. 415]. The differences between the artistic systems of Kurmangazy and Dauletkerei reflect distinct modes of relating the individual to time and sonic experience. This approach allows the analytical study of the *kui* to be connected to a broader understanding of the dombra as a mediator of cultural memory and traditional worldview [2, p. 36; 3, p. 159].

Thus, within the Kazakh tradition, the dombra functions not only as a musical instrument, but also as a mechanism of cultural thinking. Through intonation, form, and movement, it models different ways of experiencing reality, uniting the stability of tradition with the variability of artistic expression. The identified differences may be schematically summarized through the functional role of intonation, which determines the type of musical temporality and the cultural-semantic orientation of artistic expression (see Table 1).

Table 1.

Comparative Models of Musical Thinking in the *Kui*s of Kurmangazy and Dauletkerei

Paradigm	Status of Intonation	Musical Time	Function
Kurmangazy (Energetic Model)	Intonation as impulse	Vectorial (directional)	Action
Dauletkerei (Reflective Model)	Intonation as inner speech	Spiral (variant–returning)	Experience

Conclusion

The present study allows the Kazakh dombra *kui* to be interpreted not merely as a genre or stylistic category, but as a form of artistic thinking. The analysis of the works of Kurmangazy Sagyrbayuly and Dauletkerei Shygaiuly demonstrates that multiple models of musical thinking are realized within a single tradition.

Despite a shared structural foundation of the *kui*, differences emerge in the modes of its artistic realization. Within the energetic paradigm, the form is articulated as directed movement oriented toward a climax, whereas in the reflective paradigm, it unfolds as a process of inward return and progressive deepening. This indicates that the distinctions between *kuyshi* extend beyond stylistic variation to encompass more fundamental mechanisms governing the organization of musical thought.

From this perspective, the dombra tradition may be understood as a space in which diverse modes of sonic engagement with the world coexist, where intonation functions not only as an element of musical language but also as a mechanism of cultural cognition. Such an approach opens new avenues for the study of the *kui* within the frameworks of musical thought theory and cultural anthropology. It also enables the analytical exploration of *kuyshi*'s artistic thinking to be correlated with broader studies of the dombra as a stable cultural concept and a medium for the transmission of historical experience [2, p. 209; 15, 246 p.].

References

1. Zhubanov, A. Kurmangazy. Almaty: Daik-Press, 2006. – 313.

2. Seidimbek, A. Küy shezhire (The genealogy of küy). Almaty: Gylym, 1997. – 224.

3. Mukhambetova, A. I. Kazakh küy: Essays on history, theory, and aesthetics. Almaty: Daik-Press, 2002. – 205.

4. Baikadamova, B. B. Functional foundations of thematic formation in Kazakh dombra music (Abstract of Candidate of Sciences dissertation). Alma-Ata, 1983. – 195.

5. Shegebayev, P. On the unity of the personal qualities of a folk musician and the stylistic features of his music (on the example of Kurmangazy). *Cultural Heritage*, (3), 2022, 46–51 p.

6. Abdirakhman, G. B. On the problem of studying the specificity of musical thinking. *Theatre. Painting. Cinema. Music,* (1), 2015, 159–172.

7. Nesipbay, R. T. Küy-tökpe in the system of traditional Kazakh worldview *(*Abstract of Candidate of Sciences dissertation). Almaty,1999. – 22.

8. Amanov, B. Zh. Compositional terminology of dombra *küys*. In A. I. Mukhambetova (Ed.), *Instrumental music of the Kazakh people* (pp. 39–48). Alma-Ata: Öner, 1985. – 39–48 p.

9. Matsievsky, I. V. *Folk instrumental music as a cultural phenomenon*. Almaty: Daik-Press, 2007. – 520.

10. Aravin, P. V. *Dauletkerey and Kazakh dombra music of the 19th century*. Almaty: Öner, 2008. – 240.

11. Mukhambetova, A. I. *Folk instrumental culture of the Kazakhs*. Alma-Ata, 1976. – 195.

11. Asafyev, B. V. *Musical form as a process* (2nd ed.). Leningrad: Muzyka, 1971. – 376.

12. Amanov, B. Zh., & Mukhambetova, A. I. Kazakh traditional music and the 20th century. Almaty: Daik-Press, 2002. – 544.

13. Merriam, A. P. The anthropology of music. Evanston: Northwestern University Press, 1964. – 358.

14. Geertz, C. The interpretation of cultures. New York: Basic Books, 1973. – 470.

15. Zhudebayev, A. A. The concept of the dombra in Kazakh folk and authorial verbal art: Cultural meanings and poetic structures. *Keruen*, 1(90), 2026, 246–265. https://doi.org/10.53871/2078-8134.2026.1-17

CHEMICAL SCIENCES

INVESTIGATION OF THE $CuInSe_2$–CoSe SYSTEM

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ABSTRACT

The nature of physicochemical interaction in the $CuInSe_2$–CoSe system was determined and its phase diagram was constructed using DTA, XRD, MSA, and microhardness measurement methods. The phase diagram of the system is of the eutectic type; the eutectic crystallizes at a temperature of 950°C and a composition of 68 mol% CoSe.

At 810°C, a chalcopyrite ⇌ sphalerite phase transition occurs in CuInSe2. High-temperature β-$CuInSe_2$ forms a eutectic with CoSe. With an increase in the concentration of cobalt selenide, the temperature of the α-$CuInSe_2$ ⇌ β-$CuInSe_2$ polymorphic eutectoid transformation decreases monotonically from 810°C to 660°C.

Solubility based on $CuInSe_2$ is 10 mol% at room temperature. X-ray diffraction patterns of the studied samples were recorded using the X-ray diffraction method on a Bruker D8 ADVANCE diffractometer.

Microstructure and microhardness analyses were performed on a PMT microscope. It was determined that the sample with a composition of 50 at.% Co + 50 at.% Se is single-phase and has a microhardness of 4850 MPa.

Keywords: eutectic, thermal effect, microhardness, phase diagram, equilibrium.

Introduction

Ternary copper chalcogenides with a chalcopyrite structure are recognized as promising photoelectric materials, and among them, $CuInSe_2$ occupies a special place. Interest in the chalcopyrite phase of $CuInSe_2$ is due to the fact that this compound and several phases based on it exhibit photoconductivity with high efficiency [1-3].

The introduction of 3d-transition metals into the structure of $CuInSe_2$ significantly alters the electrophysical and optical properties of the parent compound; for example, its electrical conductivity can increase by several orders of magnitude [4-14].

The production of homogeneous alloys based on $CuInSe_2$ with the participation of 3d-transition metals is of great importance. For instance, in [15-17], certain complex phases possessing magnetic ordering at high temperatures were obtained based on the Cu–In–Cr–Se (Te) system.

We have previously studied the $CuInSe_2$–MeSe systems (where Me = Mn, Fe, Ni). In the present work, the nature of the physicochemical interaction in the $CuInSe_2$–CoSe system was determined and its phase diagram was constructed using DTA, XRD, MSA, and microhardness measurement methods. This paper presents a finalized version of the phase diagram for the $CuInSe_2$–CoSe system, with refined boundaries of solid solutions from the $CuInSe_2$ side.

Experimental part

Samples of the system were synthesized from high-purity elements (electrolytic copper with an impurity content of less than 0.0001%, In-000 grade indium, OSCh-17-4 selenium, and carbonyl cobalt) in evacuated (~0.1 Pa) quartz ampoules with a gradual increase in temperature up to 1100°C and, in some cases, even higher. The duration of the synthesis was at least 8 hours. To achieve an equilibrium state, the alloys were subjected to homogenizing annealing at 630°C for 100 hours. DTA of the alloys was performed on an N-307/1 two-coordinate potentiometer. A differential-combined version of a chromel-alumel thermocouple was utilized. Calcined Al_2O_3 served as the reference standard. The amount of the alloy sample was generally 1 g. However, in certain cases, to resolve the degeneracy of thermal effects of neighboring phase transitions, the mass of the analyzed samples was reduced to 0.2 g. The results of the DTA and microhardness measurements for the $CuInSe_2$–CoSe system are presented in Table 1.

Table 1.

Results of DTA and microhardness measurements of the $CuInSe_2$–CoSe system

Composion				Thermal effects, ^0C		Hμ ; MPa	
mol% CoSe	amount of CuInSe2 and CoSe in 1 gram,q			Isothermal	Polythermal		
	$CuInSe_2$	Co	Se			$CuInSe_2$	CoSe
0	1,0000	0	0	810; 986	-	2200	-
5	0,9788	0,0090	0,01210	-	765; 990	2450	-
10	0,9564	0.0186	0.02495	-	775; 970; 985	2580	-
20	0,90702	0.03974	0.05324	-	725; 960; 980	2580	-
30	0,85054	0.06388	0.08558	660	955; 975	2580	-
40	0,78533	0.09175	0.12292	660; 950	975	2575	-
50	0,70920	0.12428	0.16652	660; 950	970	2580	-
60	0,61918	0,16275	0,21807	660; 950	965	2560	-
70	0,51105	0,20896	0,27999	660; 950	970	-	4850
80	0,37877	0,26550	0,35573	660; 950	995	-	4850
90	0,21321	0,33625	0,45054	660	1020	-	4850
100	-	0,42737	0,57263	1055	-	-	4850

Phase diagram of the $CuInSe_2$–CoSe system, constructed based on the combined data of the above-mentioned physico-chemical analysis methods, is shown in Fig. 1.

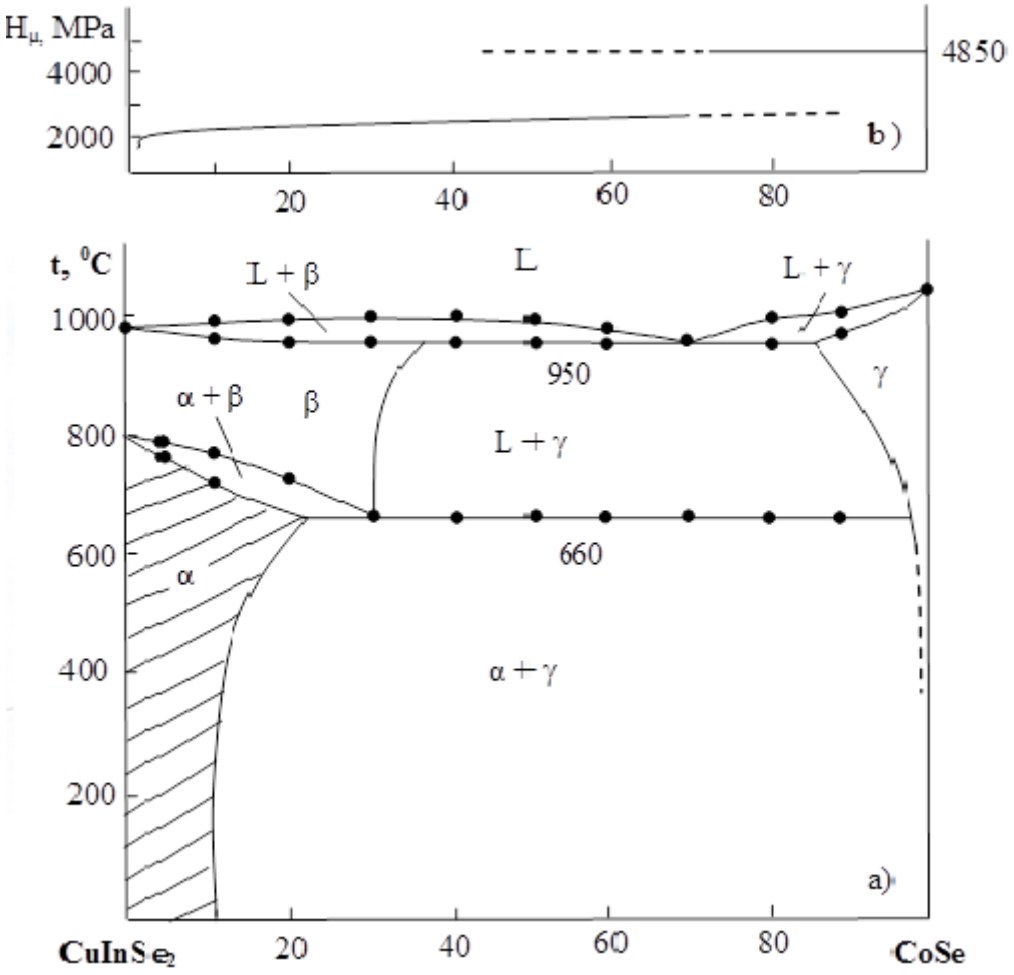

Fig. 1. a) Phase diagram of the $CuInSe_2$–CoSe system. b) Dependence of microhardness on composition.

As can be seen, the phase diagram belongs to the eutectic type with limited solubility. It is known that the sphalerite–chalcopyrite phase transition for the compound $CuInSe_2$ occurs at 810 °C. The high-temperature modification β-$CuInSe_2$ forms a eutectic with CoSe.

The eutectic crystallizes at 950 °C and 68 mol.% CoSe. With increasing CoSe concentration, the temperature of the polymorphic eutectoid transformation α-$CuInSe_2$ ⇄ β-$CuInSe_2$ decreases monotonically from 810 to 660 °C.

The solubility based on $CuInSe_2$ extends up to 22 mol.% at 660 °C and narrows to ~10 mol.% CoSe at room temperature. In the subsolidus region, the alloys consist of a mechanical mixture of α- and γ-phases. Fig. 1b shows the dependence of microhardness on the composition of chalcopyrite phases in the $CuInSe_2$–CoSe system.

It should be noted that the thermal effects at 507 °C and 910 °C reported in [18] for the alloy 50 at.% Co + 50 at.% Se were not observed by us. As noted in [18], the alloy with 50 at.% Se is heterogeneous and consists of a mixture of Co_9Se_8 and the γ-phase.

Table 2 shows the literature and our data on the values of d_α and $I_{rel.}$ for the CoSe compound.

Table 2.

Values of d_α and $I_{rel.}$ of the CoSe compound.

Our data			Data [18]		Data [21].	
d_α ,A^0	$I_{rel.}$	hkl	d_α ,A^0	$I_{отн}$	d_α ,A^0	$I_{отн}$
5,08	13		3,62	11	2,05	100
3,00	46		3,10	11	2,40	50
2,68	100		2,65	94	1,71	50
2,38	12		2,30	17	1,07	100
2,02	62		2,10	14	0,96	100
1,84	15		1,98	100	1,08	50
1,80	46		1,78	50	0,99	50
1,74	9		1,50	22		
1,45	22					
1,33	17					

However, the alloy of 1:1 composition synthesized from carbonyl cobalt is homogeneous and consists of a single γ-phase. The thermo gram of this alloy shows one thermal effect at 1052 ± 3 °C. This reversible effect corresponds to the melting temperature of CoSe [19]. The homogeneity of this alloy is confirmed by XRD, MSA, and microhardness measurements.

The X-ray diffraction patterns of the studied samples were obtained using a Bruker D8 ADVANCE. The diffraction patterns of the initial compounds were compared with literature data [20–22].

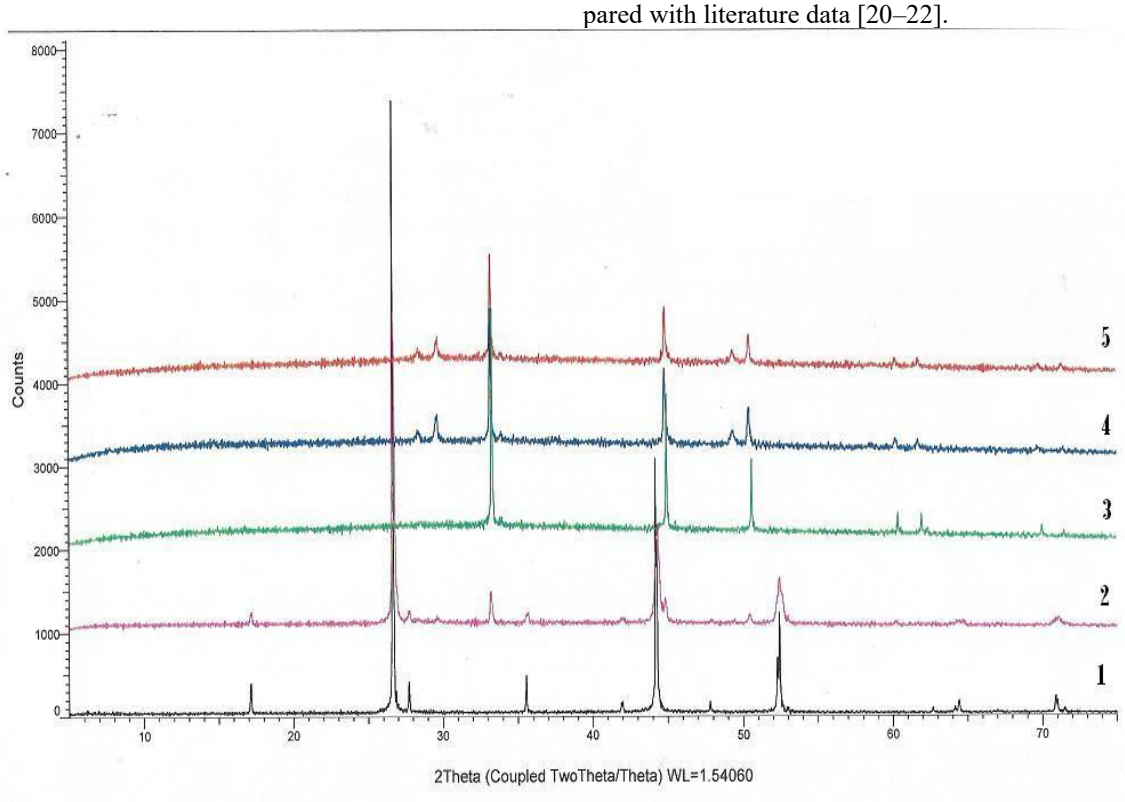

Fig. 2. X-ray diffraction patterns of alloys in the system: 1 – $CuInSe_2$; 2 – 5

Fig. 2. Diffraction patterns of alloys of the system: 1-$CuInSe_2$; 2-5 mol % CoCe; 3-10 mol % CoCe; 4-50 mol % CoCe; 5-CoSe.

The X-ray diffraction pattern of the $CuInSe_2$ compound corresponds to its chalcopyrite modification [20] with tetragonal lattice parameters a = 0.578 nm and c = 1.1621 nm. The results of the X-ray phase analysis are presented in Fig. 2. The presence of solubility is confirmed by the shift of diffraction peaks toward higher angles.

Microstructural analysis is used to identify the studied phases and determine their boundaries. This analysis, like other physico-chemical methods, helps to interpret the results of thermal analysis [23–25].

Microstructural analysis is usually carried out at room temperature in reflected light using metallographic microscopes. For this purpose, we used an MIM-7 microscope. Microhardness measurements were performed using a PMT-3 instrument.

First, microsections were prepared. The sample surface was polished by rubbing in one direction with different grades of abrasive paper. Then the surfaces were cleaned of dust and polished to a mirror finish using diamond pastes of various grades and GOI paste. The prepared microsections were first treated with water, then with alcohol or acetone, and dried. In some cases, the phases composing the samples differ only slightly in color and may appear as a single phase under the microscope. In such cases, the presence of a second phase is determined using various etching agents. In our study, a chromium-containing mixture diluted in a ratio of 1:3 (15 ml H_2SO_4 + 0.5 g $K_2Cr_2O_7$ + 50 ml H_2O) or a mixture of 1N NaOH + 3% H_2O_2 was used.

The choice of etchant and proper indentation are of great importance in microhardness measurement and microstructural analysis. The correct selection of load is essential for accurate determination of microhardness. It has been established that microhardness depends directly on the applied load on the indenter; however, the nature of this dependence has not been fully studied [26,27]. The load is selected according to the individual properties of the initial substances and the new phases formed in each system. The etching time is determined experimentally; in our work, it was approximately 5–15 seconds.

Microstructural analysis is also used to determine the homogeneity limits of solid solutions. It was established that the alloy with a composition of 50 at.% Co + 50 at.% Se is single-phase, and its microhardness is 4850 MPa (load 50 g). In the α-solid solution region, the microhardness varies from 2200 to 2580 MPa. On the CoSe side, the microhardness (4850 MPa) does not change, indicating the absence of $CuInSe_2$ solubility in CoSe at room temperature.

Thus, the $CuInSe_2$–CoSe system is quasibinary and of the eutectic type. On the $CuInSe_2$ side, there is a significant region of solid solutions, where the electrical conductivity of the samples increases sharply with increasing CoSe concentration.

Conclusion

Physicochemical studies have established that the $CuInSe_2$–CoSe system is quasi-binary and eutectic. On the $CuInSe_2$ side, there is a significant region of solid solutions, where the electrical conductivity of the samples increases sharply with increasing CoSe concentration.

References

1. Modern Problems of Semiconductor Photoenergy. Translated from English by S. Fonash et al.; edited by T. Coutts and J. Meakin. Moscow: Mir, 1988, 307 p.

2. Romanova O.B., Aplesnin S.S., Gadzhiev T.M. Photoinduced changes in impedance and conductivity of $CuInSe_2$ films depending on their synthesis technology. Solid State Physics, 2025, vol. 67, no. 10.

3. Esman A.K., Zykov G.L., Potachits V.A. Modeling of characteristics of a solar cell based on $CuInSe_2$. Proceedings of the 11th International Scientific and Technical Conference “Instrument Engineering – 2018”, pp. 279–280.

4. Olekseyuk I.D., Parasyuk O.V., Dzham O.A., Piskach L.V. The quasi-binary $CuInSe_2$–CdSe system. Phase diagram and crystal structure of solid solutions. Journal of Solid State Chemistry, 2006, vol. 179, no. 1, pp. 315–322.

5. Vakulovich A.P., Olekseyuk I.D. Phase equilibria in the $CuInSe_2$–$GeSe_2$ and $CuInSe_2$–Cu_2GeSe_3 sections of the quasi-ternary Cu_2Se–$GeSe_2$–In_2Se_3 system. Journal of Alloys and Compounds, 2004, vol. 367, no. 1–2, pp. 47–48.

6. Roussel O., Ramdani O., Chassaing E. et al. First stages of $CuInSe_2$ electrodeposition from Cu(II)–In(III)–Se(VI) acidic solutions on polycrystalline Mo films. Journal of The Electrochemical Society, 2008, vol. 155, no. 2, pp. 141–147.

7. Konstantin Gartsman, David Cahen. Extended stable junction regions in $CuInSe_2$ thin films by electric field application. Thin Solid Films, 2003, vol. 431–432, no. 5, pp. 284–288.

8. Abdullaev M.A., Magomedova J.Kh., Gadzhieva R.M. et al. Influence of deviations from stoichiometry on the electrical conductivity and photoconductivity of $CuInSe_2$ crystals. Semiconductors Physics and Technology, 2001, vol. 35, no. 8, pp. 906–908.

9. Matiev A.Kh., Georgobiani A.N., Kodin V.V., Matiev M.A. Charge transport mechanisms and magnetoresistance in $CuInSe_2$. Bulletin of the Russian Academy of Sciences: Physics, 2010, vol. 74, no. 9, pp. 1382–1383.

10. Shklovskii B.I., Efros A.A. Electronic Properties of Doped Semiconductors. Moscow: Nauka, 1979, 416 p.

11. Street R. Semiconductors. Moscow: Foreign Literature Publishing House, 1982, 467 p.

12. Malsagov A.U. Investigation of electrophysical properties of $CuGaSe_2$, $CuInSe_2$, $CuAsSe_2$ compounds in solid and liquid states. Semiconductors Physics and Technology, 2000, vol. 4, no. 8, pp. 689–691.

13. Abdullaev M.A., Magomedova J.Kh., Gadzhieva R.M. et al. Influence of deviations from stoichiometry on electrical conductivity and photoconductivity of $CuInSe_2$ crystals. Semiconductors Physics and Technology, 2001, vol. 35, no. 8, pp. 906–908.

14. Magomedov M.-R.A., Ismailov Sh.M., Magomedova J.Kh., Khokhlachev P.P. Thermoelectric and

photoelectric properties of $CuInSe_2$/CdS p–n heterostructures obtained by quasi-equilibrium deposition. Semiconductors Physics and Technology, 2000, vol. 34, no. 6, pp. 689–691.

15. Abdullaev M.A., Kamilov I.K., Magomedova J.Kh., Khokhlachev P.P. Effect of thermal oxidation on the electrical conductivity and photosensitivity of In_2O_3/$CuInSe_2$ structures. Inorganic Materials, 2007, vol. 43, no. 12, pp. 1424–1428.

16. Koneshova T.I., Marushkin K.N., Shumilkin N.S., Ellert O.G., Novotortsev V.M. Conditions for obtaining and magnetic properties of solid solutions based on $CuInCr_2Se_5$. Doklady RAS, 2002, vol. 387, no. 5, pp. 651–653.

17. Koneshova T.I., Shumilkin N.S., Novotortsev V.M. On the existence of ternary magnetic phases in the In–Cr–Te system. Inorganic Materials, 2003, vol. 39, no. 4, pp. 422–424.

18. Shumilkin N.S. Interaction in Cu–In–Cr–Se(Te) systems in the region of existence of magnetic phases with high magnetic ordering temperatures (Tc). Abstract of PhD thesis in Chemistry. Institute of General and Inorganic Chemistry RAS, Moscow, 2002, 23 p.

19. Jafarov Ya.I., Zamani I.S., Babanly M.B. Refinement of the phase diagram of the Co–Se system. In: Proceedings of the III Republican Conference "Physico-chemical analysis and inorganic materials science". Baku, 1997, pp. 126–129.

20. Phase Diagrams of Binary Metallic Systems: Handbook. In 3 volumes. Vol. 1. Edited by N.P. Lyakishev. Moscow: Mashinostroenie, 1996, 992 p.

21. Joint Committee on Powder Diffraction Standards. Powder Diffraction File, card No. 15-464.

22. Joint Committee on Powder Diffraction Standards. Powder Diffraction File, card No. 23-209, 1999.

23. Joint Committee on Powder Diffraction Standards. Powder Diffraction File, card No. 9-233.

24. Krimer B.I., Panchenko E.V., Shishko L.A. et al. Laboratory Practice in Metallography and Physical Properties of Metals and Alloys. Moscow: Metallurgiya, 1966, 248 p.

25. Panchenko E.V. Laboratory Metallography. Moscow: Metallurgiya, 1966, 248 p.

26. Glazov V.M., Vigdorovich V.N. Microhardness of Metals and Semiconductors. Moscow: Metallurgiya, 1969, 248 p.

27. Bulychev S.I., Alekhin V.P. Testing of Materials by Continuous Indentation. Moscow: Mashinostroenie, 1990, 224 p.

28. Rogacheva E.I., Tavrina T.V., Galkin S.N. Dependence of microhardness on the load applied to the indenter. Inorganic Materials, 2000, vol. 36, no. 2, pp. 173–176.

ECONOMIC SCIENCES

MONETARY POLICY TRANSMISSION AND BANK FUNDING COSTS: PANEL DATA EVIDENCE FROM AZERBAIJAN'S BANKING SECTOR

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DOI: 10.5281/zenodo.20456850

ABSTRACT

This study analyzes the impact of monetary policy and macroeconomic factors on bank funding costs in Azerbaijan using panel data covering the period from 2014Q1 to 2025Q3. The dataset includes bank-specific variables such as funding rate, lending rate, liquidity ratio, total assets, capital adequacy ratio, and leverage ratio, alongside macroeconomic variables including policy rate, inflation, devaluation dummy, and liquidity coverage ratio (LCR).

The study applies panel data regression techniques, including fixed and random effects models, followed by the Hausman Test to determine the most appropriate specification. To address endogeneity and heteroskedasticity issues, a two-stage least squares (2SLS) model with lagged instrumental variables is employed, particularly for the 2014–2017 subperiod characterized by economic crisis and currency devaluation.

The results indicate that the relationship between policy rate and funding rate deviates from standard economic theory during crisis periods. Specifically, an increase in policy rate is associated with a decrease in bank funding costs, reflecting banks' strategic behavior to maintain profitability under adverse conditions. Devaluation periods also show a significant negative impact on funding rates. The findings suggest that monetary policy transmission is weak or distorted during periods of macroeconomic instability.

Overall, the study highlights the importance of structural conditions, banking sector behavior, and macroeconomic shocks in shaping monetary policy effectiveness.

Keywords: Monetary policy; Funding rate; Panel data; Banking sector; Devaluation; 2SLS; Azerbaijan; Financial stability; Policy rate; Endogeneity

Introduction

Monetary policy transmission is a central topic in modern macroeconomic and financial analysis, as it determines how policy decisions made by central banks affect real economic activity and financial markets. One of the key channels of this transmission mechanism operates through the banking sector, where changes in policy rates influence banks' funding costs, lending behavior, and overall financial stability. Understanding the relationship between policy instruments and bank-level responses is particularly important in economies that are exposed to external shocks and structural transformations.

In Azerbaijan, the banking sector plays a dominant role in financial intermediation, making it a critical channel for the implementation of monetary policy. Over the past decade, Azerbaijan has experienced several significant macroeconomic changes, including sharp fluctuations in global oil prices, currency devaluations, and structural reforms in the financial sector. These developments have had a profound impact on the behavior of banks and the effectiveness of monetary policy transmission.

The period between 2014 and 2025 is particularly important for analyzing these dynamics. The 2014–2017 period was marked by declining oil prices and significant devaluation of the national currency, which led to increased financial instability and pressure on banks' balance sheets. The subsequent period, 2017–2022, reflects a recovery phase in which the banking sector gradually stabilized and adjusted its strategies, including a shift toward de-dollarization. More recently, the 2022–2025 period has been characterized by digital transformation, increased adoption of financial technologies, and improvements in banking sector performance.

These structural and macroeconomic changes suggest that the relationship between monetary policy and bank funding costs may vary significantly across different periods. Traditional economic theory predicts a positive relationship between policy rates and bank funding costs; however, this relationship may weaken or even reverse under conditions of financial stress, uncertainty, or institutional constraints.

Against this background, this study aims to analyze the impact of monetary policy and selected bank-specific and macroeconomic variables on the funding costs of banks in Azerbaijan. The study utilizes panel data covering multiple banks over a quarterly period from 2014Q1 to 2025Q3, allowing for both cross-sectional and time-series analysis. By incorporating variables such as liquidity ratios, capital adequacy, leverage, inflation, and devaluation effects, the study seeks to provide a comprehensive understanding of the factors influencing bank funding costs.

Literature Review

The econometric analysis of panel data has become a fundamental approach in empirical research, particularly in studies examining relationships across both cross-sectional units and time. The works of leading scholars such as Badi H. Baltagi, Jeffrey M. Wooldridge, William H. Greene, Manuel Arellano, and Richard Blundell and Stephen Bond provide the theoretical and methodological foundation for modern panel data analysis.

Badi H. Baltagi (2021) presents a comprehensive framework for panel data econometrics, emphasizing

the advantages of combining cross-sectional and time-series data. According to Baltagi, panel data allows researchers to control for unobserved heterogeneity across entities, improve estimation efficiency, and capture dynamic adjustments over time. His work highlights the importance of model selection between fixed effects and random effects, as well as the use of statistical tests such as the Hausman Test to determine the most appropriate specification.

Similarly, Jeffrey M. Wooldridge (2010) provides an in-depth treatment of cross-sectional and panel data methods, with a strong focus on practical implementation and addressing common econometric problems. Wooldridge emphasizes issues such as heteroskedasticity, autocorrelation, and endogeneity, which are frequently encountered in panel datasets. He also discusses instrumental variable techniques, including two-stage least squares (2SLS), as effective solutions for dealing with endogenous regressors.

William H. Greene (2018) further expands on these concepts by providing detailed explanations of linear and nonlinear panel data models. Greene's work is particularly valuable for understanding the assumptions underlying econometric models and the consequences of model misspecification. He highlights the importance of diagnostic testing and robustness checks to ensure the reliability of empirical results.

The contribution of Manuel Arellano (2003) is especially significant in the context of dynamic panel data models. Arellano introduces estimation techniques that account for lagged dependent variables and unobserved individual effects, which are common in financial and macroeconomic studies. His work laid the foundation for generalized method of moments (GMM) estimators, widely used in panel data analysis to address endogeneity and dynamic relationships.

Building on this, Richard Blundell and Stephen Bond (1998) developed advanced dynamic panel data estimation methods, particularly the system GMM estimator. Their approach improves efficiency by combining equations in levels and first differences, while addressing issues related to weak instruments and initial conditions. This methodology is particularly useful in studies where explanatory variables are potentially endogenous and where persistence over time is significant.

Overall, the literature demonstrates that panel data econometrics provides a robust framework for analyzing complex relationships involving multiple entities over time. The combination of fixed and random effects models, instrumental variable techniques, and dynamic estimators allows researchers to address key econometric challenges such as heterogeneity, endogeneity, and serial correlation. These methodological contributions form the basis for empirical studies examining monetary policy transmission, banking behavior, and financial stability.

Methodology

This study employs a quantitative econometric approach using panel data analysis. The dataset consists of cross-sectional units (banks) and time-series observations (quarterly data from 2014Q1 to 2025Q3).

The empirical analysis begins with panel regression models, including fixed effects and random effects estimations. The Hausman Test is applied to determine the appropriate model specification.

To address econometric issues such as heteroskedasticity and endogeneity, the study applies a two-stage least squares (2SLS) estimation technique. Lagged variables of inflation and exchange rate are used as instrumental variables to isolate exogenous variation in policy rate and devaluation effects.

Additionally, the dataset is divided into three subperiods (2014–2017, 2017–2022, 2022–2025) to capture structural changes in the banking sector and evaluate differences in monetary policy transmission across economic phases.

Findigs and discussion The focus will be on analysis of econometric results based on panel data. Panel dataset have cross-sectional entities (banks) and time dimension, which are banks and quarterly data spanning from 2014Q1 to 2025Q3, respectively.

Panel dataset consists of bank specific and macroeconomic variables such as funding rate, lending rate, ratio of liquid-to-total assets, total assets, capital adequacy ratio and leverage ratio for banks and policy rate, devaluation dummy variable and liquidity coverage ratio (LCR). Bank specific variables have been extracted from banks' financial statements in their website. Macroeconomic variables, on the other hand, have been extracted from the website of Central Bank of Azerbaijan Republic. Devaluation dummy is assigned 1 if the period covers devaluation period of AZN against dollar and assigned 0 devaluation period is not covered. LCR dummy is assigned 1 for the period that LCR requirement was approved by central bank and 0 for the period that LCR requirement has not been applied to banking sector.

Selection of explanatory variables is based on both theoretical grounds, expert judgement and scientific literature covering this topic. Liquid-to-total-assets variables was chosed based on expert judgement basing on the fact that banks with higher liquid assets ratio are less responsive to monetary policy decisions of central bank and use their own capital to meet their day-to-day liquidity needs and expand lending. Capital adequacy ratio demonstrates sustainable capital position of the banking sector and signals if bank is healthy enough to absorb potential losses. Banks with higher CAR tend to have lower funding costs since such banks are perceived to be less risky. Leverage ratio primarily affects bank's funding cost through liquidity channel, as banks with lower leverage ratios have capital constraints and policy rate hike is more likely to increase their funding costs after market borrowing. Inflation variable is also used in the model which shows annually adjusted inflation on a monthly basis. Devaluatio dummy is used since historical experience shows that monetary policy becomes ineffective during devaluation period like in Latin American countries in 1980s. LCR dummy is used to capture its effect on banks' funding costs. As banks aim to protect LCR, they may need short-term liquidity needs to avoid macroprudential tool violation and meeting such needs may increase banks' funding costs.

As the dataset is explained with its variables and coverage of time period, we should now continue with econometric analysis observe how policy rate and abovementioned variables affect funding costs of banks. We will use "Jupyter" tool of Python programming language to run necessary models and tests.

Firstly, we will set our dataset as panel data and use panel data regression to see how variables respond to each other. Since it is panel data regression, we will do both fixed and random effects regression and use hausman test to see which model is more suitable to continue with. After identification of which model to use, we will firstly use regression for whole period to identify the relationship of independent variables on funding costs.

In the next step of our model, we will firstly decide how to proceed with our model. Since our data spans from 2014 to 2025 and Azerbaijan had different economic periods during this decade, it would be better to analyze model by dividing into different periods and see the mechanical changes in different periods through model results. To capture structural changes over time, full sample was split into three subperiods: 2014-2017, 2017-2022, 2022-2025.

Azerbaijan's 2014-2017 economic period is characterized by falling oil prices, increasing policy rates, huge capital loss of financial institutions, with some banks even experiencing default. Banks needed capital to cover their losses and manage foreign currency-denominated loans, while households utilized maximum amount of their credit lines to meet their daily needs and Central bank played an important role to stabilize the economy by providing liquidity to banks and rose the policy rate to alleviate inflation pressure. However, the effectiveness of policy rate changes' reflection on banks is another question to be investigated.

The 2017-2022 economic period of Azerbaijan features the recovery period of Azerbaijan's banking sector. During this period, banks experienced growth phase in their total assets after two consecutive devaluation periods, which increased risky assets, non-performing loan ratios and loss on revenue. During recovery period, non-performing loans ratios of banks declined compared to spiking ratios of devaluation period and banks started to follow de-dollarization strategy to hedge their assets and liabilities against potential currency devaluations. Starting from recovery period, banks started to offer low interest rates for deposits and as a result, dollarized deposits' share started the period of decline. Banks also became discouraged to lend in foreign currency since this carries currency devaluation risk within itself.

2022-2025 period of Azerbaijan's banking sector is deeply characterized by adoption of technological solutions offered by banks. These technological innovations include digital payments, enhanced control on customers' accounts and online lending and deposit services through banks' digital applications. The availability and advertisement of such services by banks enabled banks to increase revenues through both traditional and digital channels. Technological advancements have made banks more visible in societal perception and these changes are reflected in more-than-forecasted increase in revenues from banks. Latest changes have made banks more financially sustainable, thereby contributing to broader financial stability.

Three different economic phases of banking sector of Azerbaijan identified above are charactarized by shifts in macroeconomic and structural conditions. These economic periods indicate varying policy implementation by regulatory authorities, alongside changing responses and incentives from households and the businesses in the economy.

We will firstly analyze Azerbaijan's 2014-2017 economic period characterized by decline in oil prices and devaluation period. Through this economic period, we will look at the relationship between policy rate and funding rate in banking sector with addition of other explanatory variables. For 2014-2017 period, two stage least squared models with lag variables were found to be the most appropriate since least squares method were found to be heteroskedastic (Figure 7).

Dependent Variable: AVERAGE_FUNDING_RATE
Method: Panel Two-Stage EGLS (Cross-section random effects)
Date: 03/10/26 Time: 16:47
Sample (adjusted): 2014Q3 2017Q4
Periods included: 14
Cross-sections included: 21
Total panel (unbalanced) observations: 290
Swamy and Arora estimator of component variances
Instrument specification: C INFLATION(-2) EXCHANGE_RATE(-1)
Constant added to instrument list

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	10.88120	0.699805	15.54891	0.0000
POLICY_RATE(-1)	-0.220452	0.022599	-9.754832	0.0000
DEVALUATION_DUM...	-2.863800	0.487733	-5.871652	0.0000

Effects Specification	S.D.	Rho
Cross-section random	2.814207	0.7237
Idiosyncratic random	1.739077	0.2763

Weighted Statistics			
R-squared	0.292664	Mean dependent var	1.155365
Adjusted R-squared	0.287735	S.D. dependent var	2.072928
S.E. of regression	1.751101	Sum squared resid	880.0443
F-statistic	160.0458	Durbin-Watson stat	0.893578
Prob(F-statistic)	0.000000	Second-Stage SSR	588.1748
Instrument rank	3		

Unweighted Statistics			
R-squared	0.115977	Mean dependent var	7.068645
Sum squared resid	3071.661	Durbin-Watson stat	0.256014

Figure 1

The figure above is the result of two-stage least squares model and the funding rate in the banking sector is explained by two variables, first of which is lagged variable of policy rate set by centrak bank and second is devaluation dummy. I have also added 2 period lag of inflation and 1 period lag of exchange rate variable as intruments. Since independent variables might be correlated with error terms, which is common in panel data regressions, instruments are employed to refine the exogenous variation in explanatory variables. Inflation and exhange rate are primary tools for the use of central bank and therefore, they are used to isolate the part of independent variables which are correlated with error term.

Inflation is used as an intrumental variable for policy rate since it is the main driver of rate decision made by central bank and primary instrument of monetary policy. 2 period lag is used to observe the policy transmission effect rather than immediate economic shocks. Exhange rate is used as an instrumental variable for devaluation dummy. By using this exchange rate as an instrumental variable, effect of currency shocks on banks' funding costs are isolated independent of fluctuations in the market which are not related to devaluation.

Now, looking at the model results, we observe that lagged policy rate variable has coefficient -.022, which means that 1% increase in policy rate is associated with 0.22% decrease in average funding rate of banking sector, which is the result against the economic theory. However, since economic theory does not always hold in real life, this coefficient can be explained by economic crisis characteristics in the country and banks' action plans regarding risk management during devaluation. During this period, banks mostly lowered their funding rate, unlike central bank, to reduce their interest expenses and widen the spread between lending and funding rates to keep their net interest income high and have cushion against potential future crisis. Looking at devaluation dummy, we observe that during the periods of devaluation which spans from 2015Q1 to 2017Q3, funding rate in the banking sector is decreased for the profitability purposes. P-values also indicate that independent variables are significant determinants of funding rate.

Besides coefficient interpretation, rho shows that 72% of the variation in funding rate emerges from the difference between banks. Probability of F-statistics is also significant which indicates that model is consistent and strong to explain the data. To see how two stage least-squares improved the model, we can look at weighted and unweighted sum of squared residuals. Looking at the result, we see that SSR is 3071 for un-

weighted statistics and reduces to 588 in weighted statistics. This shows that two stage least squares model significanly improved the noise in the data and made the estimates more consistent. R-squared for the model covering mainly devaluation period is 29%, which is considered decent amount of variation explained for panel data models.

Discussion

The findings reveal that monetary policy transmission in Azerbaijan's banking sector is highly dependent on macroeconomic conditions. During the 2014–2017 crisis period, characterized by oil price shocks and currency devaluation, the relationship between policy rate and funding cost deviates from theoretical expectations.

The negative coefficient of the policy rate suggests that banks responded strategically by lowering funding costs to maintain profitability and manage risks. This behavior reflects the dominance of internal banking strategies over external monetary signals during crisis periods.

The significant impact of the devaluation dummy further confirms that macroeconomic shocks play a crucial role in shaping banking behavior. In addition, high rho values indicate that a large portion of variation in funding costs is explained by differences across banks, highlighting structural heterogeneity within the banking sector.

The use of instrumental variables improves model reliability, as shown by the reduction in the sum of squared residuals. However, the relatively moderate R-squared value suggests that other unobserved factors may also influence funding costs.

Conclusion

The study concludes that monetary policy transmission in Azerbaijan is not uniform across different economic periods. During times of financial instability and currency devaluation, traditional monetary policy tools lose effectiveness, and banks adjust their behavior based on internal risk management strategies rather than external policy signals.

The results demonstrate that structural factors, banking sector characteristics, and macroeconomic shocks significantly influence funding costs. Therefore, relying solely on policy rate adjustments may not be sufficient to control financial conditions during crisis periods.

Overall, the study highlights the need for a more comprehensive and flexible monetary policy framework that accounts for structural and behavioral dynamics within the banking sector.

References

1. Baltagi, B. H. (2021). *Econometric Analysis of Panel Data*. Springer.
2. Wooldridge, J. M. (2010). *Econometric Analysis of Cross Section and Panel Data*. MIT Press.
3. Greene, W. H. (2018). *Econometric Analysis*. Pearson.
4. Arellano, M. (2003). *Panel Data Econometrics*. Oxford University Press.
5. Blundell, R., & Bond, S. (1998). Initial conditions and moment restrictions in dynamic panel data models. *Journal of Econometrics*, 87(1), 115–143.
6. Huseynova, S. M., & Hajizada, T. J. (2024). Analysis of the Stability of the Banking Sector of Azerbaijan in Conditions of Economic Crisıs Based on the Econometric Model. *Статистика и экономика*, *21*(2), 35-49.
7. Huseynova, S., & Balajayeva, L. (2025). Digital Banking Regulation in Azerbaijan: Empirical Insights into User Trust, Risk Management, and Data Protection. *Journal of Eastern European and Central Asian Research (JEECAR)*, *12*(2), 80-97.
8. Гусейнова, С. М., & Нволиса, Н. (2026). Оценка влияния инвестиций и цен на нефть на торговый баланс между Азербайджаном и Россией с использованием эконометрических методов. *Статистика и Экономика*, *23*(1), 82-90.
9. Huseynova, S. M., & Gambarli, U. A. (2023). Cointegration and causality relationship of the USA stock market with selected world markets. *Бізнес Інформ*, (12), 128-134.
10. S. Huseynova and M. Charkasov, "Long-run Relationship Between Türkiye and SHANGHAI Cooperation Organization Stock Markets: Cointegration Analysis", *JSAS*, no. 10, pp. 1–9, Dec. 2024, doi: 10.52693/jsas.1472756.
11. Hüseynova, Sara. "Kapsayici Kalkinma Göstergelerinin Ekonomik Kalkinma Üzerindeki Etkisi." *Scientific Collection «InterConf+»*, no. 30, Feb. 2023, pp. 28-31, doi: 10.51582/interconf.19-20.02.2023.004.
12. Elvin Alirzayev & Sara Huseynova, 2025. "Empirical Evidence Of J-Curve Effect and Marshall Lerner Condition: Case of Azerbaijan," The Scientific-Analytical Journal "Economic Reforms", Center for Analysis of Economic Reforms and Communication of the Republic of Azerbaijan, vol. 2025(1), pages 40-56, June.
13. Huseynova, S., & Kazimov, J. (2025). Investment Incentives as a Tool for Sustainable Economic Development in the Azerbaijan Republic. *International Research Journal of Economics and Management Studies IRJEMS*, *4*(11).
14. Central Bank of the Republic of Azerbaijan. Statistical Bulletins and Monetary Policy Reports.

THE ESSENCE OF CONFERENCE TOURISM, ANALYSIS OF THE STATE AND PROSPECTS OF ITS DEVELOPMENT IN AZERBAIJAN

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ABSTRACT

This study examined the development of conference tourism in Azerbaijan and its impact on the country's economy. Conference tourism diversifies the economy and tourism sector of the country, creates new jobs and strengthens international relations by organizing international events and attracting participants to the country. It is noted that in order to accelerate the development of this type of tourism, it is necessary to continuously improve infrastructure, expand cooperation with various regional and international organizations, and monitor international experience.

Keywords: Azerbaijan, conference tourism, international organizations, multifunctional halls.

Introduction. Azerbaijan's tourism sector is developing rapidly. Various government measures and successful tourism strategies are being implemented for the dynamic development of the national tourism industry, including various types and forms of tourism. In this regard, certain types of tourism are developing, one of which is conference tourism. At the same time, it should be noted that the potential of conference tourism in the country has not yet been fully utilized in the tourist cycle. The organization of international events and conferences is important for economic diversification, balanced regional development and recognition of the organizational and economic potential of Azerbaijan in the field of conference tourism development in the global market. The development of conference tourism can also have a significant impact on the economic and cultural life of the country. Thus, the development of conference tourism will both strengthen the global political, economic and cultural integration of Azerbaijan, and increase additional foreign exchange earnings, since conference tourism is one of the most profitable types of tourism.

The object of the research is the conference tourism system in Azerbaijan, including its development within the framework of the country's tourism sector, infrastructure and international integration.

The subject of the research is the organizational and economic issues that arise in the process of organizing and developing conference tourism in Azerbaijan.

The purpose of the study. To conduct research and present scientifically and theoretically sound proposals for the development of conference tourism in Azerbaijan.

Scientific novelty of the research. As a result of the study, it was found that Azerbaijan has favorable conditions and the necessary potential, which creates the basis for the development of conference tourism. However, this potential has not yet been fully exploited. For the development of this type of tourism, it is necessary to take additional measures to create a new infrastructure for the effective use of opportunities and potential, improve the skills of conference tourism organizers, expand international cooperation and exchange experience. Theoretically and empirically sound proposals have been put forward to address these issues.

The information base of the study is formed by data and reports from the State Tourism Agency of Azerbaijan, the State Statistical Committee and various institutions, information about organized and planned international organizations, conferences and events, and research materials on the relevant topic.

Methodology and research methods. The methodological basis of the research is a systematic approach to the problem. The research used methods of analysis, comparison, generalization, statistical analysis, synthesis and deduction.

Discussion. Tourism, as in many countries, is one of the types of economic activity that plays an important role in the socio-economic development of Azerbaijan and provides a substantial impetus to the overall development of the national economic system [2]. Taking this factor into account, in the "Azerbaijan 2030: National Priorities of socio-economic Development" adopted in 2021, the tourism sector is among the eight important and priority areas of strategic economic development of Azerbaijan [1]. The natural tourist resources available in the country, the social and special tourist infrastructure, which has been constantly updated and improved in recent years in accordance with modern requirements, as well as other favorable conditions create favorable conditions for the diversified development of national tourism [3]. In particular, the growth of economic potential against the background of the overall development of Azerbaijan has raised financial support to a high level, which is one of the important factors of development, and has further expanded the real opportunities for the integrated development of tourism.

Currently, a number of types of tourism are developing and gaining popularity in the system of tourist services. One of these types is conference tourism. The opportunities for the development of this type of tourism in Azerbaijan are considerably broad. Conference tourism is a type of tourism that occurs for the purpose of people traveling to other countries in connection with international conferences, seminars, exhibitions and other events. Conference tourism is also important

as an important type of tourism that strengthens the economy, culture and international relations of the country, and its development gives a powerful impetus to the overall development of the national tourism industry.

The accelerated development of the national economy in recent years has allowed Azerbaijan to strengthen its influence and ranking in the world, strengthen its economic potential and penetrate the sphere of interests of many political, economic and cultural centers. This necessitated the regular organization of international events of various levels and orientations in Azerbaijan, including conferences on various topics and events. Increasing the intensity of organizing such events provides a substantial impetus to the development of conference tourism in Azerbaijan, as conference tourism is considered and developed as one of the means of organizing various local, regional and international events and meetings.

Such events attract tourists to the country, contributing to the development of both the economy and the strengthening of international relations. Azerbaijan has repeatedly organized events of the "Organization of Turkic States" (OTS), the "Organization of Islamic Cooperation" (OIC), and the "Commonwealth of Independent States" (CIS), as well as successfully hosted international events and conferences dedicated to solving global environmental problems and other topics, such as COP 29. These events provide Azerbaijan with new opportunities to gain international recognition, expand new channels of cooperation, strengthen the economy and create conditions for the accumulation of certain experience. In addition, such events contribute to the creation and continuous improvement of high-level infrastructure, give an impetus to improving the quality of tourist services, as well as the production and supply of new types of services.

In general, Azerbaijan has broad opportunities, natural, economic and infrastructural potential for the organization and development of various types of tourism and pursues a targeted policy for the rational use of this potential [4].

The results of the discussion. The development of conference tourism in Azerbaijan has been growing rapidly in recent years due to various factors. There are several key factors in the development of conference tourism in Azerbaijan. First of all, Azerbaijan's geographical location and strategic importance make the country an ideal venue for international events. In addition, Baku, Ganja, Gabala and other cities, being hubs for international flights, provide convenient conditions for guests to travel to the conference.

Baku is the most important center of Azerbaijan both economically and in terms of tourism. The well-developed infrastructure, modern conference centers and hotels in Baku create a very favorable and suitable environment for world-class events. At the same time, Azerbaijan's successful integration into global processes, the developing common infrastructure and the serious transformation and development of the tourism sector have created additional incentives for holding international events. International events and conferences held in Azerbaijan also play an important role in the international recognition of the country and the expansion of its relations.

In addition, by providing a commendable example and experience in organizing and holding international events at a high level, Azerbaijan creates incentives for participation in international events in countries around the world and organizations at various levels. This also creates a serious demand for the organization of conferences on various topics in the country. Consequently, the number of conferences held in Azerbaijan in this field has been steadily increasing in recent years. The dynamics of this growth is reflected in the figure 1.

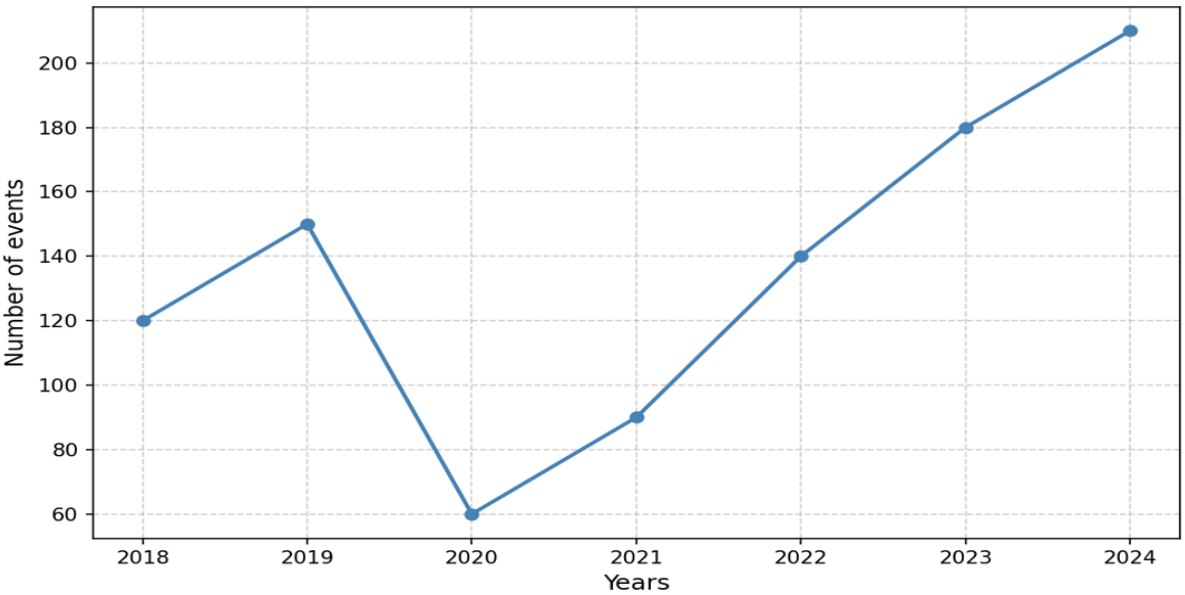

*Figure 1. The dynamics of events at various levels held in Azerbaijan in 2018-2024. *Built by the authors on the basis of statistical data from the State Tourism Agency [10].*

As can be seen from graph 1, there has been an increase in the number of conferences and other similar events organized since 2018. In 2019, the introduction of restrictions related to the risks caused by the COVID-19 pandemic led to a serious reduction in the

organization of international events, and only 60 international events on various topics were held in the country. Starting in 2020, the number of international events is increasing annually, reaching 210 in 2024. The growing number of conferences devoted to international and regional issues is an indicator of the development of conference tourism in Azerbaijan. Thus, the policy pursued in the field of organization and development of conference tourism continues successfully and considerable promise.

It should be noted that Azerbaijan regularly hosts summits of the Organization of Turkic States (OTS), conferences of the Organization of Islamic Cooperation (OIC), various events of the Commonwealth of Independent States (CIS) and other conferences on international issues. The largest international conference on global climate change, COP 29, was also held in Baku in 2024.

The Organization of Turkic States is an international organization established with the aim of developing political, economic and cultural cooperation between the Turkic-speaking states. The foundation for the establishment of the organization was laid by the Nakhchivan Agreement, signed by the Turkic-speaking states on October 3, 2009 in Nakhchivan, Azerbaijan. The original name is the Cooperation Council of Turkic-speaking States (Turkic Council). Later, at the Istanbul summit in 2021, the organization's name was officially changed to the Organization of Turkic States [5; 9].

Regular conferences of the Organization of Turkic States are organized, in which Azerbaijan actively participates. The organization's international conference, held in Baku in 2023, was attended by government agencies, heads of the Organization of Turkic States, heads of historical cities and reserves of Turkic states, experts and representatives of international organizations with which the Organization cooperates, as well as representatives of the press. The Baku Declaration on the Protection of Turkic Monuments of the Organization's member states was signed at the international conference. The main goal of the declaration is to expand cooperation in the field of joint assistance to the protection, restoration and popularization of cultural heritage among historical cities and reserves of the member and observer countries of the Organization of Turkic States. Within the framework of the conference, experts from historical cities and reserves of the Organization of Turkic States member countries and representatives of international organizations visited the fortress cities of Icherisheher, Shusha and Shaki and got acquainted with historical monuments, as well as restoration work carried out in the post-war period.

The Organization of Islamic Cooperation (OIC) is an international organization created to strengthen cooperation between Muslim countries. The OIC was founded in 1969 at a summit held in Rabat, Morocco. The main reason for the creation of the organization was the arson of the Al-Aqsa Mosque in 1969. This incident showed the importance of uniting Muslim countries and developing a common position. The main goals of the organization are to develop political, economic and cultural cooperation between the member states, strengthen Islamic solidarity and protect the interests of Muslim peoples, promote international peace and security, support the position of Muslim countries on the Palestinian issue and promote cooperation in the field of education, science and technology [8].

Today, the Organization of Islamic Cooperation (OIC) is one of the largest international organizations in the world. The Organization of Islamic Cooperation (OIC) Conferences are one of the most important international events bringing together 57 member countries from all over the world. Economic, political, social and cultural issues are discussed at these events. Azerbaijan's close cooperation with the OIC and the holding of such conferences in the country demonstrate that Azerbaijan plays an important role in solving socio-economic, cultural, environmental and other problems of the Islamic world and in the overall integration process.

The Commonwealth of Independent States (CIS) was established on December 8, 1991 in Belovezhskaya Pushcha in Belarus on the basis of the Belovezhskaya Agreements signed by the leaders of Russia, Ukraine and Belarus. This agreement actually formalized the collapse of the Union of Soviet Socialist Republics. Later, at a meeting held in Almaty on December 21, 1991, other former Soviet republics joined the CIS, and the organization's activities expanded. The CIS was established in 1991 after the collapse of the USSR to maintain political, economic and humanitarian ties between the newly independent states [6; 7].

The Commonwealth of Independent States (CIS) Conferences are a platform for discussing political, economic, security and other issues of countries located in the post-Soviet space. Azerbaijan is an active member of the CIS, and the activities of this organization are aimed at ensuring the stability and development of the region. To date, Azerbaijan has hosted a number of CIS conferences. Examples include the “Conference on Management of Science and Technology”, “Conference on Oil Refining and Petrochemistry”, “Conferences of banking organizations of the CIS countries2, etc. Such conferences play an important role in the country's international relations and strengthen Azerbaijan's position as an influential force in the region.

One of the international events organized at a high level and successfully completed in Baku was the “Conference of the Parties” (COP), where issues of combating global climate change were discussed. The “Partners Conference”, which joined the Convention, aims to solve quite significant problems. The COP, whose secretariat is located in Bonn, is the highest decision-making body of the United Nations Framework Convention on Climate Change. Every year, representatives of governments from all over the world gather at COP to call for joint efforts to prevent and eliminate the effects of climate change.

Azerbaijan hosted COP-29 in 2024. The 11-day conference focused on the experiences and traditions formed by COP-29 in the field of sustainable development and combating climate change at the local and global levels. The conference was attended by delegations from 198 countries that signed the UN Framework Convention on Climate Change.

Azerbaijan's successful organization of international events, along with an increase in the country's tourism revenues, creates conditions for the development of business ties with local economic entities. These events also put Azerbaijan in the spotlight as one of the successful organizers of international events in the region and in the world.

Conference tourism has a significant impact not only on the development of tourism, but also on the local economy. The conference participants consumption of accommodation, food, and transportation services, as well as the purchase of local products, revitalize the local economy, provide employment, and increase the flow of foreign currency into the country. Assessing the impact of conference tourism on the country's economy, we argue that the development of this type of tourism leads to the development of local businesses and the creation of new jobs.

In addition, the development of conference tourism accelerates the development of other service sectors. The development of conference tourism contributes to the development of the country's tourism infrastructure and stimulates activities related to the construction and use of new facilities in the tourism industry, multifunctional conference halls. This process has a positive impact not only on the tourism sector, but also on the development of sectors directly and indirectly related to the hospitality industry.

There are also some difficulties preventing the faster development of conference tourism in Azerbaijan. Strengthening cooperation with international organizations and other experienced organizers of conference tourism will help overcome difficulties in this area, solve problems, raise organizational issues to a higher level and accelerate the more successful development of this type of tourism. At the same time, it is very important to train experienced and professional conference organizers and train specialists in this field. Studying international experience and adapting this experience to local conditions is essential for the effective development of conference tourism.

The increased interest in the development of conference tourism in Azerbaijan in recent years further enhances the potential of national tourism. The favorable strategic and geographical location of the country, the development of modern infrastructure and the expansion of international relations create additional prospects for Azerbaijan in hosting international conferences and events. The development of this type of tourism will contribute to both the diversification of the tourism sector and the development of other sectors of the economy.

Holding international conferences on various issues in Azerbaijan, including events such as COP 29, enhances the country's international prestige and creates an opportunity to establish mutually beneficial high-level relations with most countries of the world. Such events have a positive impact not only on the development of tourism, but also on the local economy, creating new jobs and stimulating the development of the local tourism services sector.

However, there are some difficulties in the development of conference tourism in Azerbaijan. In order to overcome these difficulties and disadvantages and effectively develop conference tourism, it is important to strengthen international cooperation in this field, enhance the experience of local specialists and constantly improve the special infrastructure of conference tourism.

In addition, increased cooperation between the public and private sectors is essential to ensure the sustainable and successful development of conference tourism. Government support in this area will ensure the attraction of international events to the country and the growth of conference tourism as a new economic opportunity for Azerbaijan. In general, the development of conference tourism in Azerbaijan will strengthen international relations and turn the country into an important tourist center in the region and around the world.

Conclusion. Conference tourism is one of the most promising and profitable types of tourism in the development of the national tourism industry. Azerbaijan has a huge potential for the organization and development of this type of tourism. Systematic measures are being implemented and conferences of various levels are being organized to make effective use of this potential. At the same time, in order to ensure the sustainable development of conference tourism in the country, it is advisable to implement the following proposals put forward by us:

-it is necessary to develop the infrastructure and create new multifunctional conference halls. The availability of high-class conference centers offering comprehensive services, modern accommodation facilities and a network of transportation services will create additional incentives for development in this area.;

-expand cooperation with international organizations. The further development of Azerbaijan's relations with international organizations will allow the country to regularly organize global events and give a sustainable character to the development of conference tourism.;

-achieve advanced training of local specialists in the field of conference tourism, ensure staff participation in trainings at leading foreign practice centers in order to increase their competence and introduce international experience in the conference organization process.

The implementation of the proposed measures will create additional incentives for the development of conference tourism, which is one of the promising types of national tourism, and will allow Azerbaijan to become one of the recognized centers of conference tourism in the region and the world.

References

1. Азербайджан 2030: Национальные приоритеты социально-экономического развития. Утверждено Указом Президента Азербайджанской Республики от 2 февраля 2021 года. Баку, 2021.

2. А.Н. Гасанов. Социально-экономическое значение и роль развития туризма в Азербайджане // Региональная экономика: теория и практика. 2013, №13, с. 62-66.

3. А.Н. Гасанов. Природные туристские ресурсы Азербайджана // Сервис plus. 2012, № 3, с. 11-15.).

4. Гасанов А.Н. Целевая государственная туристская политика важный элемент развития туристской индустрии Азербайджана // Austria Science. İnnisbrug, 2017, №10, с. 60-64.

5. Organization of Turkic States. Organization_of_Turkic_States. 2024. https://www.turkicstates.org.

6. Encyclopaedia Britannica. Commonwealth of Independent States. 2021. https://www.britannica.com/topic/Commonwealth-of-Independent-States.

7. GKToday Commonwealth of Independent States (CIS). 2023. https://www.gktoday.in/commonwealth-of-independent-states/.

8. Organisation of Islamic Cooperation. Charter of the Organisation of Islamic Cooperation. 1969. https://www.oic-oci.org/en.

9. Organisation of Turkic States. History of the Organization of Turkic States. 2003. https://turkicstates.org/en.

10. https://tourism.gov.az/page/statistics

IMPROVING THE MANAGEMENT METHODOLOGY OF INDUSTRIAL ENTERPRISES IN THE CONTEXT OF DIGITAL TRANSFORMATION

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ABSTRACT

In the context of globalization and the accelerated development of digital technologies, industrial enterprises must adapt existing management systems to the modern requirements of the digital economy. This article examines the theoretical and practical aspects of improving industrial enterprise management methodology in the context of digital transformation. Modern digital technologies influencing production processes, organizational structure, and management decisions are examined. Particular attention is paid to the implementation of artificial intelligence systems, big data, the Industrial Internet of Things (IIoT), ERP systems, and digital platforms. Directions for improving the efficiency of industrial enterprise management through digitalization are proposed.

Keywords: digital transformation, industrial enterprise, management, digital technologies, ERP system, innovation, industry, automation, digital economy.

1. Introduction.

The current stage of global economic development is characterized by the intensive implementation of digital technologies in all areas of economic activity. Industrial enterprises are becoming key participants in digital transformation, as industry forms the foundation for economic growth, innovative development, and increased national competitiveness.

In the context of digitalization, approaches to managing production systems are changing significantly. Traditional management methods no longer provide the necessary flexibility, speed of decision-making, and resource efficiency. This necessitates improving industrial enterprise management methodology using modern digital tools and technologies.

Digital transformation involves not only the automation of individual processes but also a comprehensive change in business models, organizational structure, decision-making systems, and corporate culture. In this context, the development of modern approaches to industrial enterprise management is particularly relevant.

2. Theoretical aspects of digital transformation of industry.

Digital transformation is the process of integrating digital technologies into all areas of an enterprise's activities, leading to qualitative changes in management systems, production, and interactions with consumers.

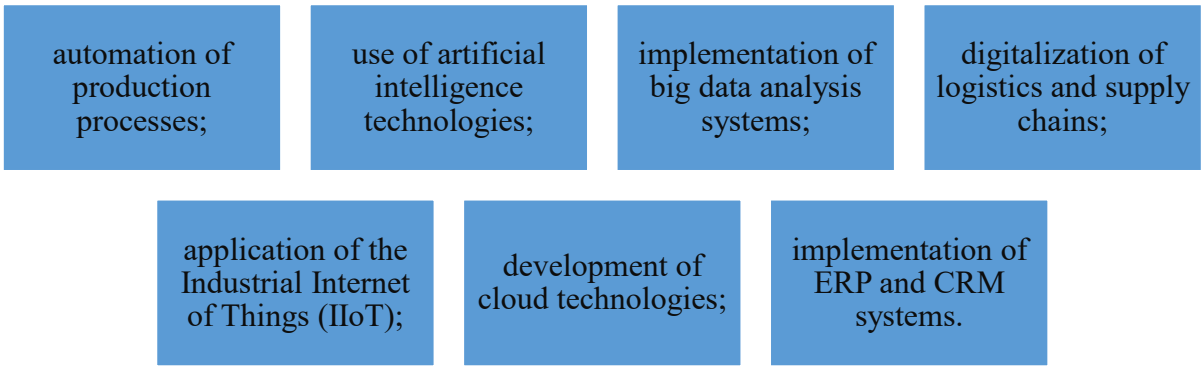
automation of production processes;
use of artificial intelligence technologies;
implementation of big data analysis systems;
digitalization of logistics and supply chains;
application of the Industrial Internet of Things (IIoT);
development of cloud technologies;
implementation of ERP and CRM systems.

Figure #1. The main components of the digital transformation of industry[1]

The digital economy is creating new demands on industrial enterprises. A modern enterprise must be highly adaptable, flexible, and able to respond quickly to changes in the external environment.

One of the key areas of digital transformation is the "Industry 4.0" concept, which involves the creation of intelligent production systems based on automation, robotics, and real-time data exchange.

Digitalization is having a significant impact on all elements of industrial enterprise management. First and foremost, it is changing management decision-making processes. Traditional management methods were based primarily on retrospective information and long-term data analysis. Modern digital technologies make it possible to obtain information in real time, predict changes, and promptly adjust management decisions.

[1]Prepared by the author.

Table #1

Major changes in the management system[2]

Process	Results
Automation of management processes	Automation reduces human error, improves operational accuracy, and lowers costs. Implementing ERP systems ensures the integration of a company's financial, production, and logistics processes.
Using Big Data	Big Data technologies make it possible to analyze vast amounts of information and identify patterns that impact production and management efficiency.
Application of artificial intelligence	Artificial intelligence helps automate analytical processes, forecast demand, optimize production cycles, and improve resource management efficiency.
Development of digital platforms	Digital platforms facilitate interaction between producers, suppliers, and consumers, creating a unified information environment.

Despite the significant benefits of digitalization, industrial enterprises face a number of challenges:

– insufficient level of digital infrastructure;
– shortage of qualified personnel;
– high costs of implementing digital technologies;
– resistance to organizational change;
– information security risks;
– insufficient integration of information systems.

One of the most serious problems is the lack of preparedness among management personnel to work in a digital economy. Effective digital transformation requires developing new competencies and a digital mindset.

To improve the efficiency of industrial enterprise management in the context of digital transformation, it is advisable to implement the following areas of improvement of management methodology.

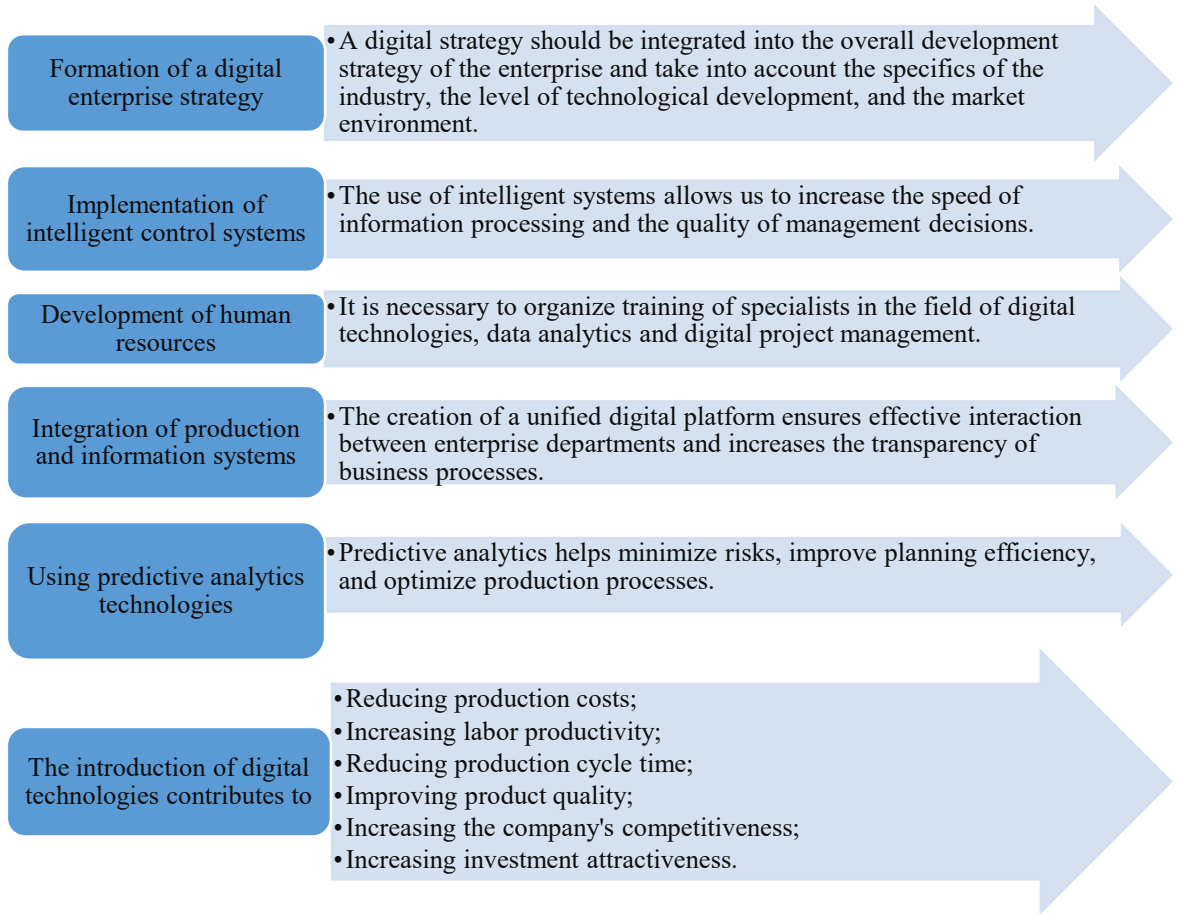
Formation of a digital enterprise strategy
• A digital strategy should be integrated into the overall development strategy of the enterprise and take into account the specifics of the industry, the level of technological development, and the market environment.
Implementation of intelligent control systems
• The use of intelligent systems allows us to increase the speed of information processing and the quality of management decisions.
Development of human resources
• It is necessary to organize training of specialists in the field of digital technologies, data analytics and digital project management.
Integration of production and information systems
• The creation of a unified digital platform ensures effective interaction between enterprise departments and increases the transparency of business processes.
Using predictive analytics technologies
• Predictive analytics helps minimize risks, improve planning efficiency, and optimize production processes.
The introduction of digital technologies contributes to
• Reducing production costs;
• Increasing labor productivity;
• Reducing production cycle time;
• Improving product quality;
• Increasing the company's competitiveness;
• Increasing investment attractiveness.

Figure #2. Factors contributing to increased efficiency in industrial enterprise management in the context of digital transformation[3]

[2]Author's development.
[3]Prepared by the author during the research.

Companies that actively implement digital technologies demonstrate higher growth rates and resilience to external economic changes.

3. Foreign experience of the research.

In global scientific and practical literature, improving industrial enterprise management methodology in the context of digital transformation is considered within the context of the concepts of "Industry 4.0," "Smart Factory," digital ecosystems, and intelligent manufacturing. Particular attention is paid to the integration of digital technologies into production processes, the improvement of strategic management systems, the development of personnel digital competencies, and the formation of flexible organizational structures.

Research by the World Economic Forum, the Organization for Economic Cooperation and Development, and McKinsey & Company has made significant contributions to the development of digital industrial transformation theory. Their studies note that digital industrial transformation involves not only the implementation of technologies but also changes to the entire enterprise management system, including organizational structure, decision-making methods, incentive systems, and corporate culture.

According to the "Industry 4.0" concept, digital transformation involves the widespread use of artificial intelligence, the Industrial Internet of Things (IIoT), big data, cloud computing, digital twins, and automated production management systems. Research shows that the implementation of these technologies can improve labor productivity, reduce production costs, reduce equipment downtime, and enhance production flexibility.

The "smart factory" approach, actively implemented in Germany, the United States, Japan, South Korea, and China, holds a special place in global practice. The German "Industrie 4.0" model views the industrial enterprise as a unified digital system, where all production processes are integrated through cyber-physical systems and intelligent control networks. The American approach emphasizes the use of platform solutions, big data analytics, and digital ecosystems to ensure enterprises are highly adaptable to market changes.

Research by the Global Lighthouse Network shows that digital transformation leaders achieve significant results through a comprehensive approach to production management based on the synchronization of business processes, technologies, and human capital. Specifically, the network's companies demonstrate increased labor productivity, reduced production costs, and increased supply chain resilience.

International researchers place particular emphasis on the human factor in digital transformation. Contemporary research emphasizes the need to shift from a purely technological approach to a human-centered model of industrial enterprise management. Within this framework, developing digital competencies among employees, providing intelligent operator support, and using augmented reality technologies in production process management are crucial.

International studies also show that successful digital transformation requires the development of a new management methodology based on:

- integration of digital technologies into strategic management;
- using real-time data;
- flexible management of production processes;
- development of platform business models;
- improving corporate governance;
- implementation of digital monitoring and forecasting systems.

At the same time, researchers note that one of the main problems of digital transformation remains the so-called "pilot trap" a situation in which enterprises successfully implement individual digital projects but are unable to scale them across the entire production system.

Global experience shows that improving industrial enterprise management methodology in the context of digital transformation should be based on the comprehensive integration of digital technologies, strategic management, innovative organizational approaches, and human capital development. This enables enterprises to ensure sustainable competitiveness, improve production efficiency, and adapt to the global digital economy.

4. Analysis and results of the study.

The research demonstrated that digital transformation has a complex impact on the management systems of industrial enterprises and is becoming a key factor in enhancing their competitiveness in the modern economy. An analysis of scientific literature, international experience, and current industrial development trends allowed us to identify key areas for improving management methodology in the context of digitalization.

The study found that the implementation of digital technologies significantly improves the efficiency of production and management processes. The use of ERP systems, Big Data technologies, artificial intelligence, the Industrial Internet of Things (IIoT), and digital platforms enables the integration of all enterprise business processes into a single information system. This significantly increases the speed of information processing, improves the quality of management decisions, and ensures operational control over production processes.

The analysis showed that digitalization contributes to:

- reduction of production costs;
- increasing labor productivity;
- reducing the time required to make management decisions;
- increasing the accuracy of planning;
- improving product quality;
- increasing the resilience of enterprises to external economic changes.

The research revealed that the most effective areas for improving industrial enterprise management are:

- automation of management processes;
- implementation of intelligent data analysis systems;
- development of digital infrastructure;

- integration of information systems;
- use of predictive analytics;
- development of digital competencies of personnel.

Research of global experience has shown that successful digital transformation requires a comprehensive approach, encompassing technological, organizational, and personnel changes. It has been established that companies implementing digital transformation systematically achieve higher economic results compared to those implementing individual digital solutions piecemeal.

At the same time, the analysis revealed a number of challenges hindering the effective digital transformation of industrial enterprises. Key issues include insufficient digital infrastructure, a shortage of qualified personnel, high costs of implementing digital technologies, information security risks, and resistance to organizational change.

The research's results confirm that improving industrial enterprise management methodology should be based on the principles of flexibility, adaptability, integration of digital technologies, and strategic management. Of particular importance are the use of real-time data, the development of intelligent decision-support systems, and the development of a digital corporate culture.

5. Conclusion.

In today's environment, digital transformation is becoming an imperative for industrial enterprise development. Traditional management methods are gradually losing their effectiveness, necessitating the development of new approaches to organizing production and management processes.

The research found that the implementation of digital technologies enables industrial enterprises to significantly improve operational efficiency, ensure resilience to external changes, and strengthen their competitive position in the market. ERP systems, artificial intelligence, Big Data, the Industrial Internet of Things, and digital platforms play a key role in improving management systems.

It has been established that successful digital transformation is impossible without a comprehensive improvement of management methodology, including:

- modernization of the organizational structure;
- development of digital competencies of personnel;
- integration of information systems;
- automation of business processes;
- improving strategic management.

Global experience shows that companies that actively implement digital technologies and modern management methods achieve higher productivity, innovation, and sustainable development.

Improving industrial enterprise management methodology in the context of digital transformation is a critical factor in increasing industrial efficiency and ensuring sustainable economic development. Prospects for further research include developing practical mechanisms for implementing digital technologies, refining strategic management models, and assessing the effectiveness of industrial enterprises' digital transformation.

References

1. Abdullaev Sh.A. Modern approaches to the management of industrial enterprises in the context of digitalization // Bulletin of Economic Research. - 2023. - No. 2. - P. 28-35.
2. Ansoff I. Strategic Management. - St. Petersburg: Piter, 2019.
3. Vikhansky O.S. Strategic Management. - Moscow: Gardariki, 2020.
4. Imomov N.N. Development of the digital economy and problems of industrial transformation in Uzbekistan // Economy and Finance. - 2021. No. 6. P. 14–21.
5. Castells M. The Information Age: Economy, Society, and Culture. Moscow: HSE, 2018.
6. Salimov B.T. Digital transformation of industry and improvement of management systems // Economy and innovative technologies. - 2022. No. 4. P. 45-53 Brynjolfsson E., McAfee A. The Second Machine Age. - New York: WW Norton & Company, 2014.
7. Brynjolfsson E., McAfee A. The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies. - New York: W. W. Norton & Company, 2014.
8. Capturing the True Value of Industry 4.0 // McKinsey & Company.
9. Davenport T. Big Data at Work. - Boston: Harvard Business Review Press, 2014.
10. Davenport TH Big Data at Work: Dispelling the Myths, Uncovering the Opportunities. - Boston: Harvard Business Review Press, 2014.
11. Digital Transformation in Manufacturing: Global Lighthouse Network. - Geneva: World Economic Forum, 2022.
12. Drucker P. Management Challenges for the 21st Century. - New York: Harper Business, 2007.
13. Gilchrist A. Industry 4.0: The Industrial Internet of Things. - New York: Apress, 2016.
14. Ivanov D., Dolgui A., Sokolov B. The Impact of Digital Technology and Industry 4.0 on the Ripple Effect and Supply Chain Risk Analytics // International Journal of Production Research. - 2019. Vol. 57. No. 3. P. 829-846.
15. Kagermann H., Wahlster W., Helbig J. Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0. - Frankfurt: Acatech, 2013.
16. Klaus Schwab. The Fourth Industrial Revolution. - Geneva: World Economic Forum, 2016.
17. Lee J., Bagheri B., Kao HA A Cyber-Physical Systems Architecture for Industry 4.0-Based Manufacturing Systems // Manufacturing Letters. - 2015. Vol. 3. – P. 18–23.
18. Matt C., Hess T., Benlian A. Digital Transformation Strategies // Business & Information Systems Engineering. - 2015. – Vol. 57. - No. 5. P. 339-343.

19. OECD Digital Economy Outlook 2020. - Paris: Organization for Economic Co-operation and Development, 2020.

20. OECD Digital Economy Outlook. - Paris: OECD Publishing, 2023.

21. Porter M., Heppelmann J. How Smart, Connected Products Are Transforming Competition // Harvard Business Review. - 2015.

22. Porter ME, Heppelmann JE How Smart, Connected Products Are Transforming Competition // Harvard Business Review. - 2014. Vol. 92. No. 11. P. 64–88.

23. Schwab K. The Fourth Industrial Revolution. - Geneva: World Economic Forum, 2016.

24. Schwab K., Davis N. Shaping the Future of the Fourth Industrial Revolution. - New York: Currency, 2018.

25. Tapscott D. The Digital Economy. - New York: McGraw-Hill, 2015.

26. Vial G. Understanding Digital Transformation: A Review and a Research Agenda // Journal of Strategic Information Systems. - 2019. Vol. 28. No. 2. P. 118-144.

27. Westerman G., Bonnet D., McAfee A. Leading Digital: Turning Technology into Business Transformation. - Boston: Harvard Business Review Press, 2014.

STATE POLICY AND INNOVATION-DRIVEN DEVELOPMENT IN KAZAKHSTAN: CONSTRAINTS AND PROSPECTS

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ABSTRACT

Purpose: This study examines how government policy shapes innovation-driven development in Kazakhstan, with a focus on systemic constraints in a transition economy.

Design/methodology/approach: The paper combines descriptive statistics, cross-country comparative analysis (OECD benchmarks), and a system-based framework of the national innovation system (NIS). A conceptual model is complemented by a parsimonious analytical specification linking innovation outcomes to R&D intensity, institutional quality, and science–industry linkages.

Findings: Kazakhstan demonstrates a persistent gap relative to OECD economies across input (R&D expenditure, human capital), throughput (university–industry collaboration), and output indicators (patents, high-technology exports). The findings suggest that low R&D intensity, weak commercialization mechanisms, and limited private-sector engagement jointly constrain innovation performance.

Originality/value: The study integrates a multi-level (macro–meso–micro) analytical perspective with a compact specification tailored to a resource-based transition economy. It contributes by identifying systemic coordination failures within the national innovation system.

Practical implications: The results highlight the need to strengthen R&D investment, improve technology transfer mechanisms, and enhance university–industry collaboration to support sustainable innovation-driven growth.

The results are robust across multiple comparative indicators.

Keywords: Innovation policy; national innovation system; R&D intensity; technology transfer; innovation performance; economic growth; Kazakhstan.

INTRODUCTION. In the context of accelerating technological change and intensifying global competition, innovation has become a key driver of long-term economic growth and structural transformation. Both advanced and transition economies increasingly rely on innovation policy to enhance productivity, diversify economic structures, and strengthen global competitiveness.

Despite a substantial body of literature on national innovation systems (NIS) and policy-driven innovation, empirical evidence from resource-dependent transition economies remains limited and fragmented, particularly with respect to the mechanisms linking public policy to measurable innovation outcomes. This limitation is especially relevant for Kazakhstan, where extensive institutional reforms and policy initiatives have been implemented, yet innovation performance remains comparatively modest (OECD, 2017; World Bank, 2020).

Kazakhstan has pursued a sequence of industrial and innovation policies aimed at technological modernization, the development of research and development (R&D), and the promotion of digital transformation. However, existing evidence points to a persistent gap between policy design and actual innovation outcomes, reflected in low R&D intensity, weak commercialization of research, and limited university–industry collaboration (Abil & Kurmanov, 2021; Kaliyeva & Kenzhegaliyeva, 2020).

These patterns suggest that innovation underperformance cannot be explained solely by resource constraints but is instead rooted in systemic inefficiencies within the national innovation system. In particular, weak coordination among key actors, insufficient integration of innovation infrastructure, and limited private-sector engagement constrain the transformation of knowledge into economic value.

Research gap. Existing studies tend to focus either on aggregate macroeconomic indicators or on isolated policy instruments, without adequately capturing the systemic interactions among institutional quality, human capital, and innovation infrastructure. As a result, there is a lack of integrated analytical frameworks capable of explaining how policy inputs translate into innovation outcomes in resource-based transition economies.

Contribution. This study makes three main contributions. First, it provides a comparative empirical assessment of Kazakhstan's innovation performance relative to OECD and selected transition economies using harmonized indicators. Second, it develops a multi-level analytical framework that integrates macro-, meso-, and micro-level determinants of innovation within the NIS perspective. Third, it proposes a parsimonious analytical specification linking innovation outcomes to key determinants, offering policy-relevant insights for improving innovation efficiency.

The remainder of the paper is structured as follows. Section 2 reviews the literature, Section 3 presents the methodology, Section 4 discusses the results, and Section 5 concludes.

LITERATURE REVIEW. The role of innovation as a driver of economic growth has been extensively examined in economic theory, particularly

within the Schumpeterian and endogenous growth traditions. Early contributions emphasize technological change as a fundamental source of structural transformation, while later developments incorporate knowledge accumulation, human capital, and institutional dynamics as key determinants of long-term growth.

Within this theoretical framework, the concept of the national innovation system (NIS) provides a systemic perspective on innovation processes, emphasizing the interactions among government, firms, and research organizations. The effectiveness of an innovation system depends not only on the presence of these actors but also on the intensity and quality of their interactions, including knowledge flows, technology transfer, and collaborative networks.

A complementary perspective is offered by the "triple helix" model, which conceptualizes innovation as the outcome of dynamic relationships among universities, industry, and government. Empirical studies consistently demonstrate that strong university–industry linkages and well-developed innovation infrastructure play a critical role in enhancing knowledge diffusion and the commercialization of research.

However, despite substantial theoretical advances, empirical evidence reveals persistent disparities in innovation performance between developed and transition economies (OECD, 2017). Resource-dependent economies, in particular, face structural constraints such as low R&D intensity, weak private-sector participation, and underdeveloped mechanisms of knowledge commercialization. These limitations reduce the capacity of national innovation systems to transform scientific potential into economically relevant outputs.

Recent contributions further emphasize the importance of institutional quality and policy coordination in shaping innovation efficiency. Fragmented policy frameworks, weak regulatory environments, and limited access to financing can significantly undermine the effectiveness of innovation policies, even when formal institutional structures are in place.

In the context of Kazakhstan, existing studies highlight the incomplete formation of the national innovation system and the persistence of structural barriers, including weak science–industry linkages and limited commercialization capacity (Alshanova & Nurlanova, 2018; Satybaldin & Mukhamediyev, 2019). These findings underscore the systemic nature of innovation constraints in transition economies.

Nevertheless, an important gap remains in understanding how these structural and institutional factors interact within resource-based, post-Soviet economies such as Kazakhstan. Much of the existing literature focuses either on aggregate macroeconomic indicators or on isolated policy instruments, with limited integration of multi-level analytical approaches capable of capturing systemic interactions.

To address this gap, the present study integrates a multi-level (macro–meso–micro) analytical perspective with comparative empirical evidence and a parsimonious specification linking policy inputs to innovation outcomes. This approach enables a more comprehensive understanding of the mechanisms through which innovation policy influences economic performance in transition economies.

METHODOLOGY. Research Design. This study employs a mixed-method analytical approach that integrates descriptive statistical analysis, cross-country comparative analysis, and system-based conceptual modeling. This combination enables a comprehensive assessment of innovation performance within the framework of the national innovation system (NIS), allowing both empirical benchmarking and structural interpretation.

Data Sources. The empirical analysis draws on data from the Bureau of National Statistics of the Republic of Kazakhstan, the World Bank, the OECD, and the World Intellectual Property Organization (WIPO). These sources provide internationally comparable indicators of innovation activity, ensuring consistency and reliability in cross-country analysis.

Analytical Framework. The study adopts a multi-level analytical framework to capture the systemic nature of innovation processes:

Macro-level: government policy, R&D expenditure, and institutional environment

Meso-level: innovation infrastructure, clusters, and venture financing mechanisms

Micro-level: firm-level investment, human capital, and absorptive capacity

This structure reflects the interdependence of actors and institutions within the NIS and allows for a more nuanced analysis of how policy inputs translate into innovation outcomes.

Analytical Specification. To structure the empirical analysis, innovation performance is represented as a function of key determinants of the national innovation system:

$$Innovation = f(R\&D, Institutions, Human\ Capital, Linkages)$$

This functional representation captures the multidimensional nature of innovation processes and emphasizes that innovation outcomes result from the combined effects of several interrelated factors.

- **R&D intensity (R&D):** reflects the scale of investment in knowledge creation.
- **Institutional quality (Institutions):** captures regulatory effectiveness and governance capacity.
- **Human capital (Human Capital):** represents the availability of skilled labor and research capabilities.
- **Science–industry linkages (Linkages):** proxy for knowledge transfer, collaboration, and commercialization.

The specification is not intended as a full econometric model but rather as a parsimonious analytical tool that guides the interpretation of empirical patterns and supports the identification of structural constraints.

Methods of Analysis. The empirical investigation employs several complementary methods. Descriptive statistical analysis is used to evaluate trends in key innovation indicators. Comparative analysis benchmarks Kazakhstan against OECD and selected transition

economies. System analysis is applied to examine interdependencies within the innovation system, while analytical generalization is used to identify structural constraints and derive policy implications.

RESULTS AND DISCUSSION. Evolution of Innovation Policy in Kazakhstan. The evolution of innovation policy in Kazakhstan reflects a gradual shift from industrial modernization toward a more comprehensive innovation- and knowledge-based development model (Table 1).

The early phase (2003–2010) focused on establishing the institutional foundations of an innovation-oriented economy, including the creation of technoparks and basic elements of innovation infrastructure. Subsequent stages increasingly emphasized industrial competitiveness, export-oriented growth, and sectoral modernization. The most recent policy agenda (2020–2025) prioritizes digital transformation, startup ecosystems, and technological entrepreneurship.

Table 1.

Evolution of state innovation policy in Kazakhstan (2003–2025)

Period	Main programs	Key objectives
2003–2010	Strategy of industrial and innovative development	Formation of the foundations of an innovative economy, diversification
2010–2014	SPFIID	Industrial modernization
2015–2019	SPIID-2	Competitiveness enhancement
2020–2025	SPIID-3	Transition to the digital economy

Source: Author's compilation based on the Bureau of National Statistics of the Republic of Kazakhstan, World Bank, OECD, and WIPO.

Despite the progressive expansion of policy instruments and institutional frameworks, measurable innovation outcomes remain limited. This suggests a persistent misalignment between policy design and implementation effectiveness. In particular, the expansion of formal institutions has not been accompanied by a corresponding increase in innovation performance indicators.

From the perspective of the national innovation system, this pattern indicates a transition from institution-building to the challenge of institutional efficiency. The presence of innovation-supporting institutions alone is insufficient; effective innovation outcomes depend on the intensity and quality of interactions among system actors, including firms, universities, and government agencies.

Consistent with previous empirical studies, Kazakhstan's innovation system remains constrained by weak institutional coordination and limited knowledge transfer mechanisms (OECD, 2017; Abil & Kurmanov, 2021). These findings suggest that the primary bottleneck lies not in the availability of policy instruments, but in the effectiveness of their coordination and implementation.

Comparative Analysis of Innovation Performance. The comparative analysis reveals a substantial and persistent innovation gap between Kazakhstan and both OECD and selected transition economies across multiple dimensions (Tables 2 and 3).

Table 2.

Comparative innovation indicators: Kazakhstan and selected countries

Indicator	Kazakhstan	Russia	Belarus	Uzbekistan	EU	USA
Share of innovatively active enterprises, %	11.9	14.5	12.1	10.8	40.3	45.2
R&D expenditures, % of GDP	0.13	1.1	0.6	0.3	2.1	3.0
Share of innovative products in GDP, %	1.37	2.5	1.8	0.9	10.5	12.1
Number of researchers per 1000 people	2.5	4.2	3.1	1.8	6.5	9.2
Patent activity, number/million people	5	20	10	3	80	110
High-tech exports, %	2.1	5.5	4.0	1.5	15.2	20.1
Venture capital financing, million $	15	250	30	5	1500	3500
The share of innovations involving universities, %	12	35	20	10	45	55
The level of digitalization of production, %	25	60	45	20	70	85
Global Innovation Index	66	45	57	75	18	3

Source: Author's compilation based on the Bureau of National Statistics of the Republic of Kazakhstan, World Bank, OECD, and WIPO.

Kazakhstan significantly underperforms relative to advanced economies across key indicators, including R&D expenditure (approximately 0.13% of GDP), the share of innovation-active firms (around 11–12%), patent activity, high-technology exports, and venture capital availability. While some progress is observable in digitalization and industrial diversification, these improvements remain insufficient to close the overall innovation gap.

Importantly, this gap is not merely quantitative but structural. OECD economies demonstrate systematically stronger performance across all stages of the innovation process: knowledge generation (R&D intensity and research capacity), knowledge diffusion (collaboration networks and infrastructure), and commercialization (patents, high-tech production, and venture financing).

Table 3.

Innovation gap between Kazakhstan and OECD countries

№	Innovation Development Indicator	Kazakhstan	Average OECD	OECD Leaders
1	R&D expenditure (% of GDP)	~0.13 %	~2.7 %	Israel, South Korea (>4%)
2	Share of innovatively active enterprises	~11–12 %	~50–55 %	Germany, Finland (>60 %)
3	Number of researchers (per 10,000 employees)	~23	~120	Denmark, Finland (~150)
4	Patents (per 1 million population)	~40	~850	USA, Japan, South Korea
5	Share of high-tech exports	~5 %	~15–20 %	South Korea, Germany
6	Share of innovative products in industry	~5 %	~25 %	Germany, Sweden
7	Venture capital investments (% of GDP)	<0.01 %	~0.3 %	USA, Israel
8	University R&D spending	~0.03 % of GDP	~0.5 % of GDP	USA, UK
9	Digitalization of business (use of digital technologies by enterprises)	~35 %	~70 %	Finland, the Netherlands
10	Place in Global Innovation Index	~80	top 30	Switzerland, Sweden

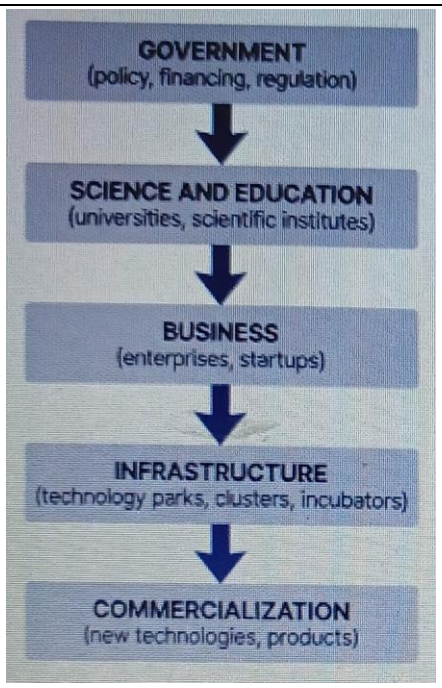
Source: Author's compilation based on the Bureau of National Statistics of the Republic of Kazakhstan, World Bank, OECD, and WIPO.

The data indicate that in several dimensions the gap reaches multiplicative differences, often ranging from five- to ten-fold, particularly in patent activity and venture capital investment. This suggests that Kazakhstan's innovation system faces not only resource constraints but also significant inefficiencies in transforming knowledge inputs into economic outputs.

From the perspective of the analytical specification proposed in this study, these findings highlight the joint impact of low R&D intensity, limited human capital utilization, weak institutional quality, and underdeveloped science–industry linkages. The interaction of these factors constrains the overall effectiveness of the national innovation system.

In terms of economic implications, such disparities are consistent with the predictions of endogenous growth theory, according to which insufficient investment in knowledge creation and weak innovation dynamics limit long-term productivity growth and structural transformation.

Structural Determinants of Low Innovation Activity. Empirical evidence, interpreted through the conceptual framework presented in Figures 1 and 2, allows the identification of key structural constraints operating across different levels of the national innovation system.

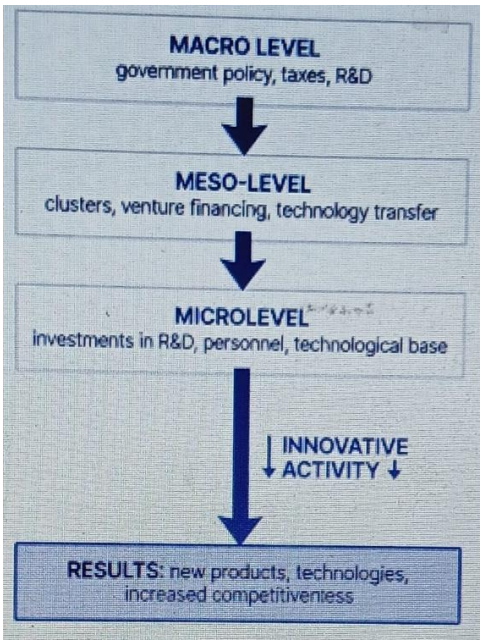


As shown in Figure 1, the structure of the national innovation system in Kazakhstan
Source: Author's elaboration

Figure 1 illustrates the institutional architecture of the national innovation system, highlighting the sequential transformation of knowledge into economic outcomes through interactions among government, science and education, business, and innovation infrastructure. This representation is broadly consistent with the "triple helix" framework, which emphasizes the role of coordinated interactions among universities, industry, and government.

However, while the model reflects a normative and well-coordinated system, empirical evidence suggests that the actual intensity of interactions among these actors in Kazakhstan remains limited. In particular, weak linkages between research institutions and the private sector constrain the effective commercialization of knowledge. This gap between institutional design and functional performance points to deficiencies in coordination mechanisms and technology transfer processes.

Figure 2 presents a multi-level framework capturing the determinants of innovation activity at the macro, meso, and micro levels. This framework enables a systematic interpretation of how policy conditions, institutional environments, and firm-level capabilities jointly shape innovation outcomes.



As shown in Figure ***2, the multi-level determinants of innovation activity***
Source: Author's elaboration

The analysis indicates that innovation performance depends critically on the consistency and complementarity of factors across all levels. Weaknesses at any level—such as insufficient venture financing, limited firm-level R&D investment, or ineffective policy coordination—can constrain overall system performance.

At the **macro level,** low public and private investment in R&D limits the scale of knowledge creation and reduces the economy's capacity for endogenous innovation. At the **meso level,** underdeveloped innovation ecosystems—particularly weak venture capital markets and insufficient technology transfer institutions—hinder the diffusion and commercialization of innovations. At the **micro level,** limited absorptive capacity and low internal R&D investment restrict firms' ability to adopt and implement new technologies.

Importantly, these constraints interact in a mutually reinforcing manner, generating a self-sustaining cycle of low innovation performance. For example, weak demand for innovation from firms reduces incentives for research institutions, while limited commercialization opportunities discourage private investment. This systemic interaction underscores the importance of coordinated policy interventions across all levels of the innovation system.

Linking Empirical Results to the Analytical Model. The empirical patterns identified above are consistent with the analytical specification introduced in the methodology. The results indicate that innovation performance in Kazakhstan is shaped by the joint influence of key determinants of the national innovation system.

In particular, **R&D intensity** remains critically low, limiting knowledge accumulation and reducing the potential for endogenous innovation. **Institutional quality** is constrained by coordination inefficiencies, which weaken the effectiveness of policy implementation. **Human capital** demonstrates moderate potential; however, its utilization remains suboptimal due to structural mismatches and limited integration with industry needs. Finally, **science–industry linkages** remain underdeveloped, significantly constraining knowledge transfer and commercialization processes.

These findings suggest that innovation performance is not determined by isolated factors but by the interaction of complementary variables. In the case of Kazakhstan, low R&D intensity interacts with weak institutional coordination and limited science–industry linkages, producing a compounded negative effect on innovation outcomes.

This interaction effect helps explain why increases in R&D expenditure alone may not lead to proportional improvements in innovation performance. Without improvements in institutional quality and linkages, additional investment in knowledge creation is unlikely to translate into economically meaningful outputs.

Overall, the innovation gap can be interpreted as the combined result of insufficient inputs and weak systemic interactions, rather than a single-factor deficiency.

Policy Implications: Toward a More Effective Innovation System. The findings suggest that innovation policy in Kazakhstan should shift from a resource-allocation approach toward a system-coordination approach. Enhancing innovation performance requires not only increased investment but also improved alignment among the key components of the national innovation system.

First, increasing R&D expenditure remains a necessary condition for strengthening innovation capacity. However, international experience indicates that the effectiveness of such investment depends on complementary institutional factors, including governance quality and coordination mechanisms.

Second, strengthening science–industry collaboration is essential for improving the commercialization of research. Enhancing linkages within the "triple helix" framework can facilitate knowledge transfer and accelerate technological diffusion.

Third, the development of innovation infrastructure—including venture financing mechanisms, clusters, and startup support systems—is critical for creating an enabling environment for innovation and entrepreneurship.

Fourth, human capital development must be aligned with the requirements of a knowledge-based economy, particularly in science, technology, and engineering fields, to ensure the effective utilization of research capacity.

Finally, improving institutional quality and policy coordination is crucial. Fragmented policy frameworks and weak regulatory environments can significantly reduce the effectiveness of innovation policies, even in the presence of increased funding.

Taken together, these measures highlight the need for an integrated and coordinated policy approach to overcome systemic constraints and enhance the overall efficiency of the national innovation system.

CONCLUSION. This study examined the role of government policy in shaping innovation-driven development in Kazakhstan within the framework of the national innovation system. The findings indicate that, despite substantial progress in establishing institutional foundations, the overall effectiveness of innovation policy remains limited in terms of measurable outcomes.

The empirical analysis reveals a persistent innovation gap between Kazakhstan and advanced economies across input, throughput, and output dimensions. In particular, low R&D intensity, weak science–industry linkages, and limited commercialization of research results continue to constrain innovation performance.

Importantly, the results demonstrate that innovation underperformance is not solely a consequence of resource constraints but reflects deeper systemic inefficiencies and coordination failures within the innovation system. The interaction of macro-, meso-, and micro-level constraints generates a self-reinforcing cycle that limits the transformation of knowledge into economic value.

This study contributes to the literature by integrating a multi-level analytical perspective with a parsimonious functional specification tailored to a resource-based transition economy. By linking empirical evidence with a systemic analytical framework, it provides

a more comprehensive explanation of how policy inputs translate into innovation outcomes.

From a policy perspective, the findings suggest that improving innovation performance requires a shift from isolated policy measures toward a coordinated and system-oriented approach. Strengthening institutional linkages, enhancing technology transfer mechanisms, and increasing the effectiveness of R&D investments are critical for overcoming structural constraints.

Finally, the results have broader relevance for other resource-dependent transition economies facing similar structural challenges. Future research may extend this analysis by incorporating econometric modeling and firm-level data to further investigate the causal mechanisms underlying innovation dynamics.

References

1. Abil, E., & Kurmanov, N. (2021). Innovation development in Kazakhstan: Trends and challenges. *Journal of Asian Finance, Economics and Business*, 8(3), 757–766.
2. Acemoglu, D., Johnson, S., & Robinson, J. A. (2005). Institutions as a fundamental cause of long-run growth. In P. Aghion & S. N. Durlauf (Eds.), *Handbook of economic growth* (Vol. 1, pp. 385–472). Elsevier.
3. Aghion, P., & Howitt, P. (1992). A model of growth through creative destruction. *Econometrica*, 60(2), 323–351. https://doi.org/10.2307/2951599
4. Alshanova, A., & Nurlanova, N. (2018). National innovation system of Kazakhstan: Current state and development priorities. *Economic Annals-XXI*, 169(1–2), 24–28.
5. Arrow, K. J. (1962). The economic implications of learning by doing. *The Review of Economic Studies*, 29(3), 155–173. https://doi.org/10.2307/2295952
6. Audretsch, D. B., & Feldman, M. P. (2004). Knowledge spillovers and the geography of innovation. In J. V. Henderson & J. F. Thisse (Eds.), *Handbook of regional and urban economics* (Vol. 4, pp. 2713–2739). Elsevier.
7. Bureau of National Statistics of the Republic of Kazakhstan. (2023). *Science and innovation indicators*. Astana.
8. Cohen, W. M., & Levinthal, D. A. (1990). Absorptive capacity: A new perspective on learning and innovation. *Administrative Science Quarterly*, 35(1), 128–152. https://doi.org/10.2307/2393553
9. Etzkowitz, H., & Leydesdorff, L. (2000). The dynamics of innovation in triple helix systems. *Research Policy*, 29(2), 109–123. https://doi.org/10.1016/S0048-7333(99)00055-4
10. Freeman, C. (1987). *Technology policy and economic performance: Lessons from Japan*. Pinter Publishers
11. Furman, J. L., Porter, M. E., & Stern, S. (2002). The determinants of national innovative capacity. *Research Policy*, 31(6), 899–933. https://doi.org/10.1016/S0048-7333(01)00152-4
12. Grossman, G. M., & Helpman, E. (1991). *Innovation and growth in the global economy*. MIT Press.
13. Hall, B. H., & Lerner, J. (2010). The financing of R&D and innovation. In B. H. Hall & N. Rosenberg (Eds.), *Handbook of the economics of innovation* (Vol. 1, pp. 609–639). Elsevier.
14. Hausmann, R., Hwang, J., & Rodrik, D. (2007). What you export matters. *Journal of Economic Growth*, 12(1), 1–25. https://doi.org/10.1007/s10887-006-9009-4
15. Hidalgo, C. A., & Hausmann, R. (2009). The building blocks of economic complexity. Proceedings of the National Academy of Sciences, 106(26), 10570–10575. https://doi.org/10.1073/pnas.0900943106
16. Keller, W. (2004). International technology diffusion. *Journal of Economic Literature*, 42(3), 752–782. https://doi.org/10.1257/0022051042177685
17. Lundvall, B.-Å. (1992). *National systems of innovation: Towards a theory of innovation and interactive learning*. Pinter.
18. Mowery, D. C., & Sampat, B. N. (2005). Universities in national innovation systems. In J. Fagerberg, D. C. Mowery, & R. R. Nelson (Eds.), *The Oxford handbook of innovation*. Oxford University Press.
19. Nelson, R. R. (1993). *National innovation systems: A comparative analysis*. Oxford University Press.
20. North, D. C. (1990). *Institutions, institutional change and economic performance*. Cambridge University Press.
21. OECD. (2017). *OECD reviews of innovation policy: Kazakhstan*. OECD Publishing.
22. OECD. (2023). *Main science and technology indicators*. OECD Publishing.
23. Porter, M. E. (1990). *The competitive advantage of nations*. Free Press.
24. Rodrik, D. (2004). Industrial policy for the twenty-first century. CEPR Discussion Paper.
25. Romer, P. M. (1990). Endogenous technological change. *Journal of Political Economy*, 98(S5), S71–S102. https://doi.org/10.1086/261725
26. Satybaldin, A., & Mukhamediyev, B. (2019). Industrial and innovative development of Kazakhstan: Problems and prospects. *Studies on Russian Economic Development*, 30(5), 514–520.
27. Schumpeter, J. A. (1934). *The theory of economic development*. Harvard University Press.
28. Solow, R. M. (1956). A contribution to the theory of economic growth. *Quarterly Journal of Economics*, 70(1), 65–94. https://doi.org/10.2307/1884513
29. UNESCO. (2021). *UNESCO science report: The race against time for smarter development*. UNESCO.
30. World Bank. (2020). *Kazakhstan: Enhancing competitiveness and innovation*. World Bank.
31. World Bank. (2023). *World development indicators*. World Bank.
32. WIPO. (2023). *Global innovation index 2023*. World Intellectual Property Organization.

ECONOMETRICAL APPROACH OF TURNOVER OF GOODS IN AZERBAIJAN'S TRANSPORT SECTOR

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Abstract

This study investigates the contribution of air transport to Azerbaijan's economic growth, especially the relationship between income and air cargo turnover. The study examines regression analysis, stationarity tests, and model diagnostics like the Durbin-Watson statistic, CUSUM stability test, and heteroskedasticity tests as a part of econometric analysis using annual data from 1996 to 2024. The results show a high positive correlation between income and air cargo turnover, the importance of regression model parameters and parameter stability. The analysis also shows that a significant increase in air transport happened after 2013, with a major rise between 2020 and 2024 because of infrastructure improvements and the post-pandemic recovery in foreign trade. Despite temporary declines, such as external shocks like COVID-19 and geopolitical concerns, the long-term trend is still good. In summary, Azerbaijan's air transport sector has been essential for improving economic performance of the country.

This study examines the turnover of goods in sea transport in Azerbaijan using econometric tools from 2001 to 2024.The research goals to evaluate the relationship between turnover of goods and expenditure of goods with some econometrics methodology, simple linear regression model and it supported by tests including importance of regression model, F-statistics and t-statistics, CUSUM and CUSUM of Squares, for defining errors heteroscedasticity analyses used White test. The statistical results indicate that model is unimportant and unstable. These limitations suggest that the current model does not adequately capture the economic dynamics of sea transportation. Also, study concludes that maritime transport plays a crucial role in the country's trade system, more advanced econometric models, methodologies and additional variables such as - price of oil, transport modes conditions and the most influential factor is the political relations between countries.

This study examines the turnover of goods in pipeline transport in Azerbaijan using econometric tools from 2000 to 2024.This research emphasizes the role of Azerbaijan in today's global oil and gas market, development of pipeline transportation and its outcomes, integration of Azerbaijan into European market, the substantial role of key routes of pipelines. It evaluates the relationship between income from transportation in the transport sector and expenditure on goods transportation in the transport sector with some econometrics methodology. It uses regression analyses, stability and heteroskedasticity tests to show importance and stability of models.

Keywords: Sea transport, air transport, pipeline transport, income, expenditure, regression equation, importance of regression model, CUSUM test, White test, Dickey-Fuller test.

Introduction

The transportation system helps foster economic growth, increase efficiency and production, and promote environmental sustainability. In other words, transportation is critical to logistics and the efficient flow of goods and resources. In fact, transportation and logistics often contribute significantly to a country's GDP while also providing national security. Efficient transportation systems can increase a country's or region's competitiveness by cutting transportation costs, expanding connectivity, and improving the speed and dependability with which goods move. Azerbaijan played a crucial role in the historic Silk Road, facilitating trade between China and Europe for centuries. The picture remains the same now. Azerbaijan serves as a balancing power between geopolitical heavyweights such as the European Union (EU) and Russia, while also strengthening economic links with China through projects such as the Belt and Road Initiative. However, in the middle of rising geopolitical tensions and economic rivalry, transportation in Azerbaijan appears to be stalled, defying aspirations and expectations for stable and upward development. Air transport contributes significantly to Azerbaijan's economic growth. The Baku-Tbilisi air route opened in 1924, providing the foundation for air travel in Azerbaijan. As the republic gains independence and expands its connections with other nations, this field is growing quickly. Azerbaijan used to have air connections with the CIS, however these days, our aircraft travel to numerous European and Asian nations.

Baku is home to the republic's most significant airport. By building a new facility on September 30, 1999, passenger services were improved and there were more options for aircraft departures. The airports at Ganja and Nakhchivan were also rebuilt.

Helicopter landing zones and the republic's airports in Ganja, Nakhchivan, Yevlakh, Sheki, Lankaran, and other places are crucial to air travel.

Aviation is used to maintain contacts with the mountainous regions, transport cargo and emergency transportation of patients, as well as to combat parasites in agriculture.

With the increase in the world population, the demand for goods and services is increasing day by day. Also, the integration of countries leads to the expansion of international transport routes. In today's world, it is impossible to imagine global trade without international modes of transport. These modes of trade are: sea, air, rail and pipeline. In this article, we will mainly focus on the Sea transport mode. Maritime transport

plays crucial role in international global trade systems. According to the UNCTAD Around 80% of the volume of international trade in goods is carried by sea, and the percentage is even higher for most developing countries. Ports are the milestones of that industry in all over the world. The busiest of these ports handle over 50 million tons of cargo annually, while approximately 15 ports manage more than 200 million tons of goods per year in terms of cargo turnover. Example for most famous ports in the world are Rotterdam, Shanghai, and Singapore. For the Azerbaijan Caspian Sea has of great importance for maritime trade. Despite having no access to the oceans, Azerbaijan is able to trade large quantities of goods with countries that have access to the Caspian Sea. The oldest and largest port in the Caspian Sea is located in the Baku Bay. İt is called “The Port of Baku”. This port is mentioned in historical documents dating back to the 16th century. It should be noted that in order to effectively use the transit opportunities of Azerbaijan, the newest and largest Baku International Sea Trade Port (BMMTP) and Free Trade Zone were built on an area of 400 hectares, 65 km south of the center of Baku, in the village of Alat. The port of Baku includes the main cargo terminal, container terminal, Dubende oil terminal (capacity up to 12 million tons), ferry terminal and passenger terminal. The ferry terminal serves the following directions: Baku-Turkmenbashi - Baku, Baku - Aktau - Baku, Baku - Iranian ports - Baku. Also, sea lines such as Baku - Makhachkala, Baku - Astrakhan, Baku - Anzali, Baku - Aktau and Baku - Mangistau are used for the transportation of oil, oil products, food and forest materials. Azerbaijan also plays an important role on the Great Silk Road. The Baku International Maritime Trade Port, plays a key role for freight from China to Europe, as well as an attractive corridor for traffic from Europe to Central Asia. The port is an integral part of the Trans-Caspian International Transport Route (TMTM), developed within the framework of the new “Great Silk Road” project. Its significance in cargo transshipment further increased with the launch of the Baku-Tbilisi-Kars (BTK) Railway on 30 October,2017.

In today’s world, pipelines are considered as cost-effective means of delivering gas and oil to consumer nations. Azerbaijan has demonstrated throughout its history that it possesses significant oil and gas reserves. Historically, Azerbaijan oil was primary goal of the Nazi Germany during world war II and forming the core of the Soviet energy system. In October 1991, Azerbaijan gained independence and since that, the country's oil industry has been in decline due to the decreasing oil production and overworked technology that required immediate investments and improvements. The oil production continued to drop until 1996 and it hit a level of almost 9 million tons annually (Gorkhmaz Askerov, 2008)

One of the most important economic decisions made in the early years of Azerbaijan's independence was the "Contract of the Century," which was signed on September 20, 1994, between the Republic of Azerbaijan and foreign oil firms. This contract represented a significant turning point in the country's economic development because it made it possible for Azerbaijan to sell its energy resources on the international market and contributed significantly to the growth of the nation's economy. The significant Azeri-Chirag-Gunashli (ACG) and Shah Deniz fields in the Caspian Sea are two of Azerbaijan's petroleum and natural gas reserves that had the potential to play a major role in the global oil and gas market. Additionally, deal turned into crucial tool for attracting foreign investment and boosting Azerbaijan's economic growth.

The construction of major export infrastructure, especially the Baku–Tbilisi–Ceyhan pipeline (BTC), which became a key route for delivering Caspian oil to global markets, was one of the agreement's primary outcomes. The pipeline begins at the Sangachal Terminal, travels through Georgia, and ends at Ceyhan Port in Turkey, which is located in the Mediterranean. The BTC pipeline improved Azerbaijan's political and economic independence, eliminated its reliance on Russian export routes, and established the nation as a key European energy hub.

Azerbaijan has also launched several main pipeline routes to diversify its energy exports and reduce dependence on a single corridor. Among the first significant oil export routes that gave access to Black Sea ports were the Baku–Novorossiysk and Baku–Supsa pipelines. Furthermore, the South Caucasus Pipeline is essential for delivering natural gas to regional markets. These pipelines, which connect Azerbaijan to Europe, are part of the larger Southern Gas Corridor, which also includes projects like the Trans-Anatolian Natural Gas Pipeline and the Trans Adriatic Pipeline.

Today, Azerbaijan’s oil and gas reserves are still able to maintain their relevance. The Russia–Ukraine war is a clear example of this. Azerbaijan emerged as one of the key alternative energy suppliers in this context. It has strengthened relations with Europe and confirmed the role of Azerbaijan in oil and gas market. The geopolitical importance of Azerbaijan and the Southern Gas Corridor only grows as Europe looks to diversify away from Russia. Another example of this is the Memorandum of Understanding (MoU) on Strategic Partnership in the sphere of Energy, which was signed on July 18, 2022, between Azerbaijan and the EU. It should be mentioned that the goal of the new Memorandum is to increase Azerbaijan's gas exports to the EU through the Southern Gas Corridor by 2027 (Fidan Namazova, 2023).

Research Questions

1.What is the relationship between the turnover of goods and income of goods in air transport in Azerbaijan during the period of 1996-2024?

2. What is the relationship between the turnover of goods and the expenditure of goods in maritime transport in Azerbaijan during the period 2001–2024?

3. What is the relationship between income of goods and the expenditure of goods in pipeline transport in Azerbaijan during the period 2000–2024?

Research Hypotheses

H_1: There is a relationship between the turnover of goods and income of goods in air transport.

H_2: There is a relationship between the turnover of goods and expenditure of goods in maritime transport.

H_3: There is a relationship between income of goods and expenditure of goods in pipeline transport.

Methodology

In this study, econometrics approach is used, specifically regression analysis, stationarity tests, model diagnostics, stability and heteroskedasticity tests. Simple linear regression model and importance of regression model is analyzed. Heteroskedasticity is examined by using the White test and for defining stationarity of time-series Dickey-Fuller test is used.

Literature review

G. Ahmadova's (2009) "Improving Air Transport Infrastructure Management" claims that modernizing the air transport complex of Azerbaijan is crucial for the implementation of the innovative model for economic growth in the country. The report explores outstanding problems with airport and ground-handling infrastructure, their current state and their management of them. By way of systems-based and economic analysis, the author argues that an increase in air facilities is necessary to protect territorial integrity and security, as well as foster socio-economic growth. Various suggestions for more effective management of infrastructure are made.

Niftiyev, I. (2024) 'Multidimensional assessment of transportation sector's performance: Nonparametric analysis of the Azerbaijani economy' indicated that the positive trajectory of the maritime, aviation, and road transport sectors underscores their potential contributions to economic growth and development. He emphasized that these sectors, displaying increasing performance potential over the years, are likely to foster trade, facilitate logistical operations, and enhance connectivity, all of which are pivotal for a thriving economy.

Imamoglu and Imanov (2008) reach the conclusion that the commercial air transport activities consume large amounts of fossil fuel and CO_2 emissions, which in general deteriorate the environment. The effect of national income, energy consumption and use of fossil fuel on environmental quality is investigated by the authors, considering the ARDL model with data covering a period of 108 quarters from 1992 to 2014. Their empirical results validate the presence of EKC for Azerbaijan.

Gorkhmaz Askerov's (2008) "OIL AND GAS PIPELINE STRATEGY OF A LANDLOCKED COUNTRY: CASE OF AZERBAIJAN" claims that Azerbaijan's strategic location and balanced foreign policy have enabled it to diversify its pipeline transport routes and reduce dependence on particularly Russia. As a result, it has gained greater advantages over its energy exports and strengthened its economic position in energy market.

Tuncay Babalı's (2005) "IMPLICATIONS OF THE BAKU-TBILISI-CEYHAN MAIN OIL PIPELINE PROJECT" discusses that BTC pipeline reshaped regional energy politics by reducing reliance on Russia and creating alternative export routes driven primarily by geopolitical interests.

Huseynova Nurana's (2025) "THE AGREEMENT OF THE CENTURY – AN INTERNATIONAL PROJECT THAT TURNS AZERBAIJAN INTO AN INTEGRAL PART OF THE GLOBAL WORLD ECONOMY" shows that ''The Contract of the Century" had a big role in transforming Azerbaijan into a strong, diversified economy while launching major projects like "BTC" and "Southern Gas Corridor".

Fidan Namazova's (2023) "UKRAINIAN WAR AND ITS IMPACT ON SOCIA-ECONOMIC SITUATION IN AZERBAIJAN" highlights the role of Azerbaijan as a major alternative energy source especially for European market after Ukrainian conflict.

Empirical results and findings

Section 1 analyzes the econometrics indicators for the period 1996-2024 based on official data from the State Statistical Committee of the Republic of Azerbaijan.

INCOME = 988.757393985*TURNOVER_OF_GOODS___AIR_ + 35101.5460531

When turnover of goods by air increases 1 unit, it means that income will increase 988,75 units

Table 1.

Result of Regression analysis

Dependent Variable: INCOME
Method: Least Squares
Date: 03/31/26 Time: 09:20
Sample: 1 29
Included observations: 29

Variable	Coefficient	Std. Error	t-Statistic	Prob.
TURNOVER_OF_GOODS___AIR_	988.7574	64.88750	15.23803	0.0000
C	35101.55	82023.55	0.427945	0.6721

R-squared	0.895832	Mean dependent var	788637.0
Adjusted R-squared	0.891974	S.D. dependent var	1072216.
S.E. of regression	352408.1	Akaike info criterion	28.44944
Sum squared resid	3.35E+12	Schwarz criterion	28.54374
Log likelihood	-410.5169	Hannan-Quinn criter.	28.47897
F-statistic	232.1974	Durbin-Watson stat	0.971568
Prob(F-statistic)	0.000000		

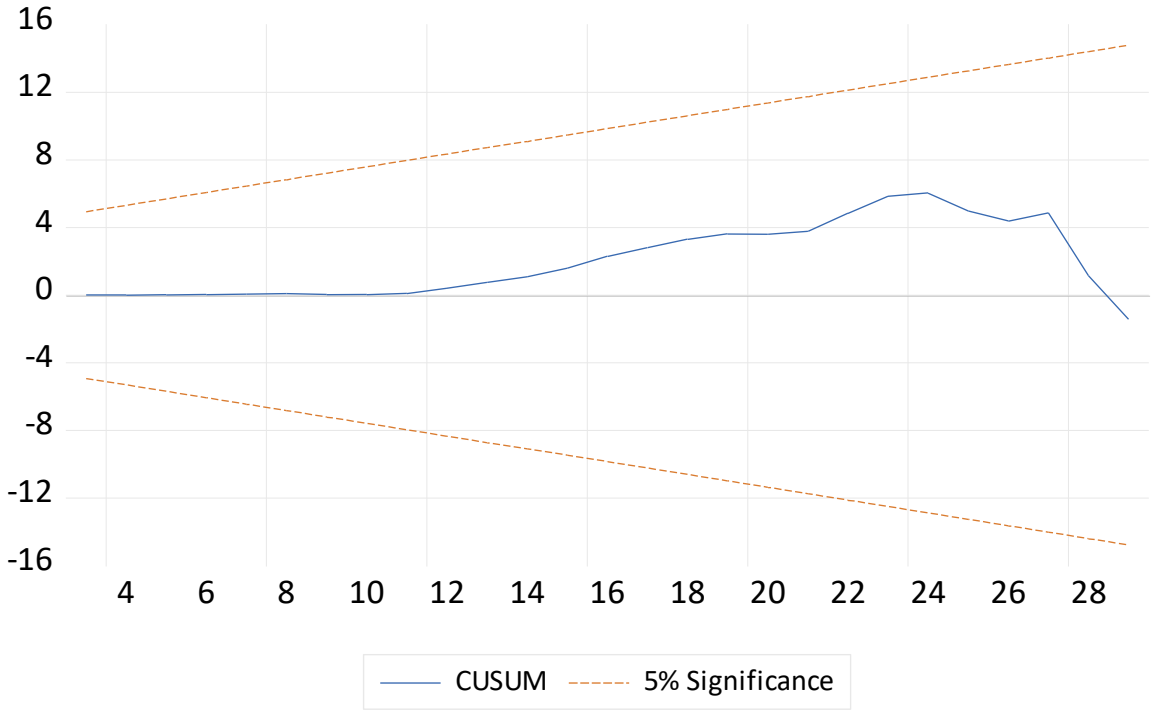
$R^2 = 0.8$, it means that turnover of goods approximate income is strong.

F-statistics = 232 F-table and Prob(F-statistic) = 0 < Prob(0.05), it means that regression model parameters are important.

Turnover of goods t-statistic (Prob) = 0 < 0.05, it means that regression model parameters are important.

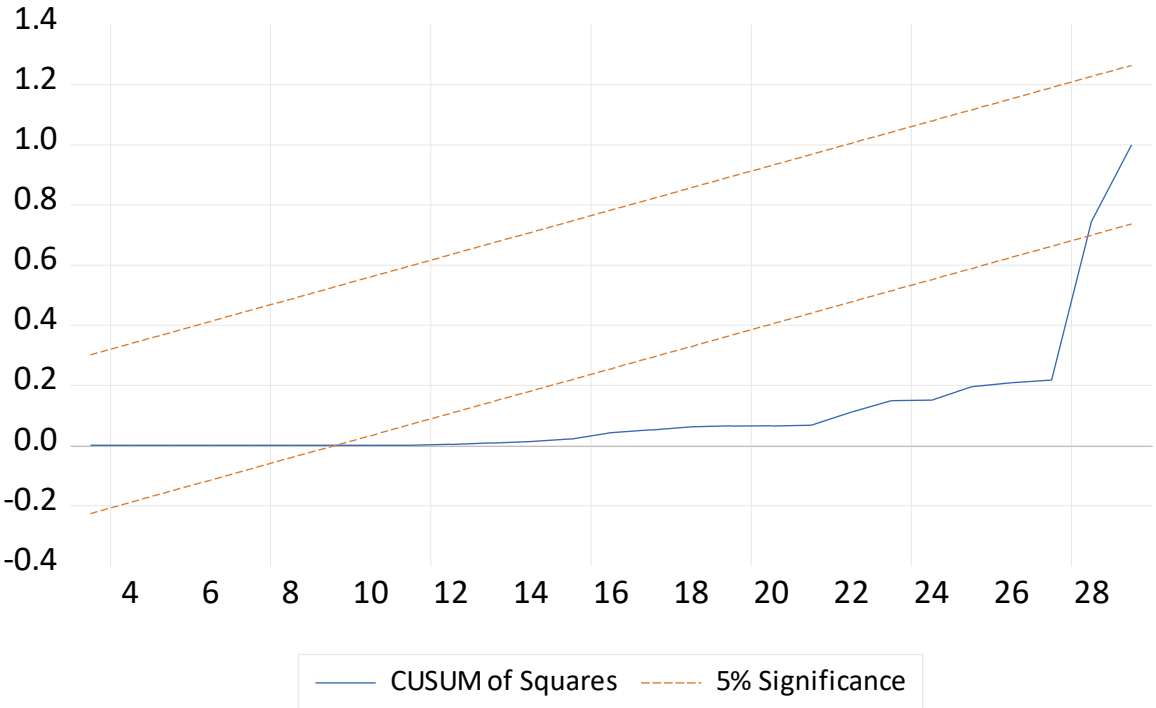
C t-statistic (Prob) = 0.6 > 0.05, it means that regression model parameters are unimportant.

Durbin-Watson stat = 0.9 < 2, it means that autocorrelation is positive.



Graph 1. Result of CUSUM test

In the graph, main line doesn't intersect border line, it means that regression model parameters are stable.



Graph 2. Result of CUSUM of Squares test

In the graph, main line doesn't intersect border line, it means that regression model parameters are stable.

Table 2.

Result of White test

Heteroskedasticity Test: White
Null hypothesis: Homoskedasticity

F-statistic	41.11211	Prob. F(2,26)	0.0000
Obs*R-squared	22.03298	Prob. Chi-Square(2)	0.0000
Scaled explained SS	29.99510	Prob. Chi-Square(2)	0.0000

F-statistic (Prob) = 0 < Prob(0.05), it means that regression model errors are heteroscedastic.

Table 3.

Result of Dickey-Fuller test

Null Hypothesis: D(TURNOVER_OF_GOODS) has a unit root
Exogenous: Constant, Linear Trend
Lag Length: 0 (Automatic - based on SIC, maxlag=6)

		t-Statistic	Prob.*
Augmented Dickey-Fuller test statistic		-4.519002	0.0067
Test critical values:	1% level	-4.339330	
	5% level	-3.587527	
	10% level	-3.229230	

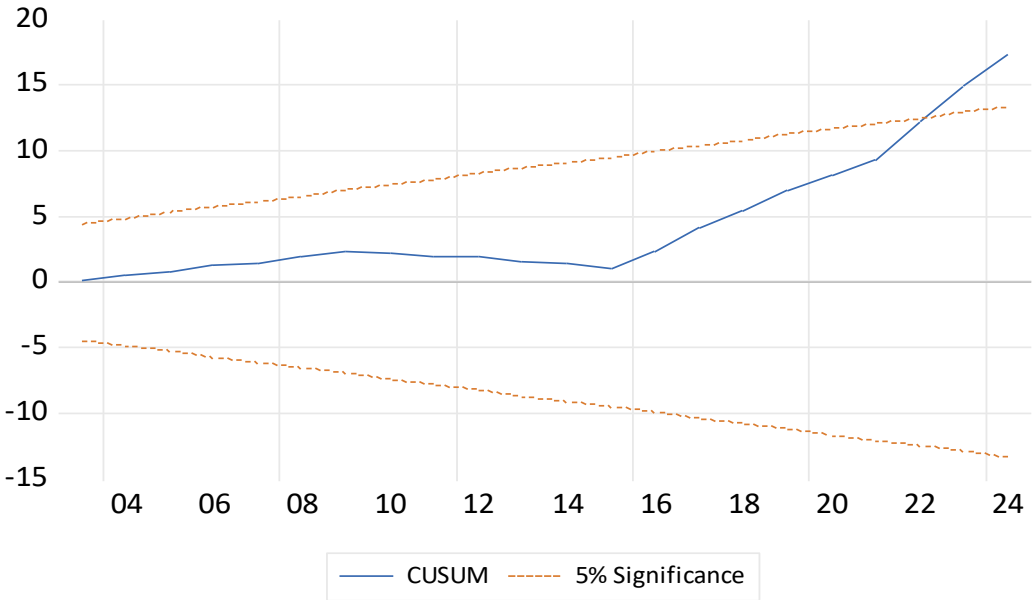
Dickey-Fuller test statistic(Prob) = 0 < 0.05 and Dickey-Fuller test statistic value = -4.5, less than test critical values (1% ,5%, 10% levels), it means that time-series are stationary.

Section 2 analyzes the econometrics indicators for the period 2001-2024 based on official data from the State Statistical Committee of the Republic of Azerbaijan.

We can see here **Simple Linear Regression** equation between Turnover of Goods (manats) and Expenditure of Goods (manats)

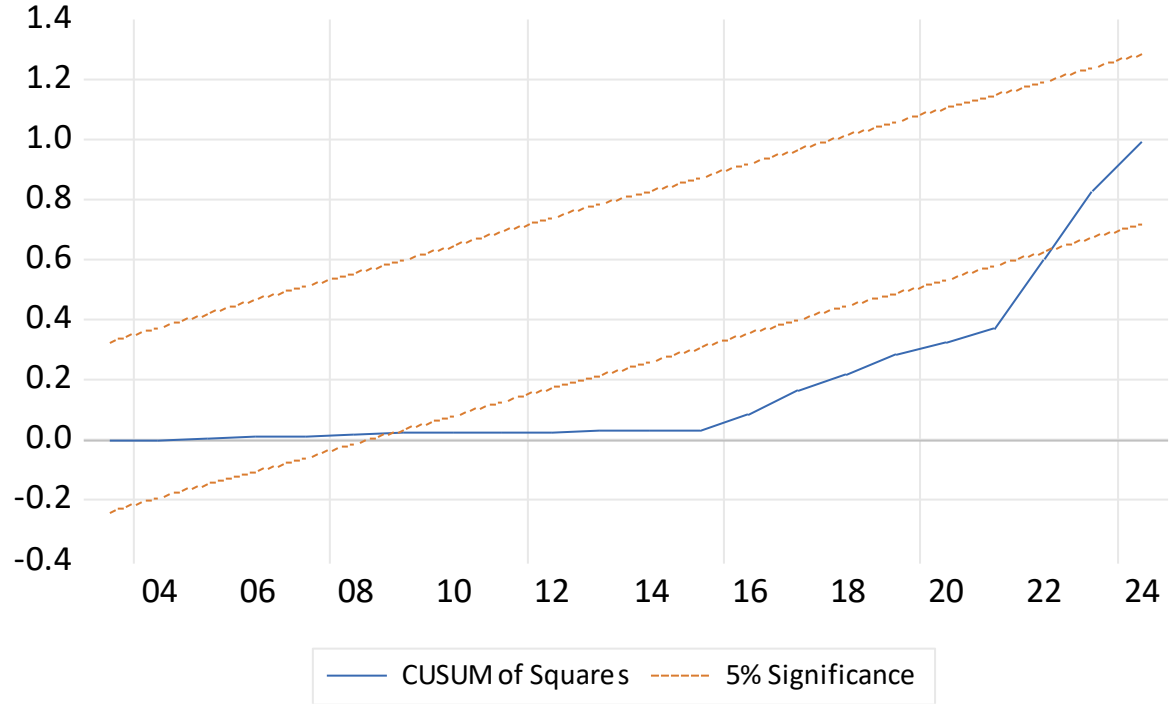
EXPENDITURE_OF_GOODS = -20.6754655358*TURNOVER_OF_GOODS + 233354.806109 (1)

The regression equation (1) is analyzed The Slope (C1 = -20.675): This represents a negative correlation. For every 1-unit increase in the turnover of goods, the expenditure on goods is expected to decrease by approximately 20.675 units, holding all else constant.R^2 = 0.367 it is more than 0.3 means that Turnover of Goods approximate Expenditure is middle.F-statistics = 12.89 and Prob(F-statistics) =0.00 < Prob(0.05) it means that regression model parameters are important Turnover of Goods t-Statistic (Prob)= 0.001 < Prob(0.05) it means that regression model parameters are important .C (constant) Prob) =0.00 < Prob(0.05) it means that , regression model parameters are important.Durbin-Watson stat. = 0.409 is less than 2 , it means that Autocorrelation is Positive



Graph 3. Result of CUSUM test

Graph 3 is shown **Main line (blue line)** does intersect with **Border lines (red lines)**, it means that regression model parameters are **unstable.**



Graph 4. Result of CUSUM of Squares test

Graph 4 result is shown that, main line (blue line) does intersect with Border lines (red lines), it means that regression model parameters are unstable.

Table 4.

Result of White test

This table is represented Regression Model Errors are **Homoscedasticity** or **Heteroscedastic**

Heteroskedasticity Test: White
Null hypothesis: Homoskedasticity

F-statistic	3.981392	Prob. F(2,21)	0.0342
Obs*R-squared	6.598358	Prob. Chi-Square(2)	0.0369
Scaled explained SS	3.873241	Prob. Chi-Square(2)	0.1442

F-statistic (Prob) = 0.0342 < Prob(0.05) it means that regression model errors are **Heteroscedastic.**

Section 3 analyzes the econometrics indicators for the period 2000-2024 based on official data from the State Statistical Committee of the Republic of Azerbaijan.

We can see here simple linear regression equation between income from transportation in the transport sector (thousand manats) and expenditure to goods transportation (thousand manats) in the transport sector.

Estimation Command:

==========

LS EXPENDITURE_TO_GOODS_TRANSPORTATION__THOUSAND_MANATS INCOME_FROM_TRANSPORTATION_IN_THE_TRANSPORT_SECTOR__THOUSAND_MANATS C

Estimation Equation:

==========

EXPENDITURE_TO_GOODS_TRANSPORTATION__THOUSAND_MANATS = C(1)*INCOME_FROM_TRANSPORTATION_IN_THE_TRANSPORT_SECTOR__THOUSAND_MANATS + C(2)

Substituted Coefficients:

==========

EXPENDITURE_TO_GOODS_TRANSPORTATION__THOUSAND_MANATS = 0.252342059306*INCOME_FROM_TRANSPORTATION_IN_THE_TRANSPORT_SECTOR__THOUSAND_MANATS - 22645.5132799

The Slope (C1) is 0.25, it represents a positive correlation. For every 1-unit increase in income from transportation, expenditure to goods transportation is expected to increase approximately 0.25 units.

Table 5.

Result of regression analysis

This table shows importance of regression model (income from transportation in the transport sector is independent variable (X) and expenditure to goods transportation (Y))

Dependent Variable: EXPENDITURE_TO_GOODS_TRANSPORTATION__T HOUSAND_MANATS
Method: Least Squares
Date: 04/21/26 Time: 10:52
Sample: 2000 2024
Included observations: 25

Variable	Coefficient	Std. Error	t-Statistic	Prob.
INCOME_FROM_TRANSPORTATION_IN _THE_TRANSPORT_SECTOR__THOUSA ND_MANATS	0.252342	0.020281	12.44240	0.0000
C	-22645.51	39580.02	-0.572145	0.5728

R-squared	0.870651	Mean dependent var	371286.2
Adjusted R-squared	0.865027	S.D. dependent var	323267.3
S.E. of regression	118764.1	Akaike info criterion	26.28428
Sum squared resid	3.24E+11	Schwarz criterion	26.38179
Log likelihood	-326.5536	Hannan-Quinn criter.	26.31133
F-statistic	154.8134	Durbin-Watson stat	1.040951
Prob(F-statistic)	0.000000		

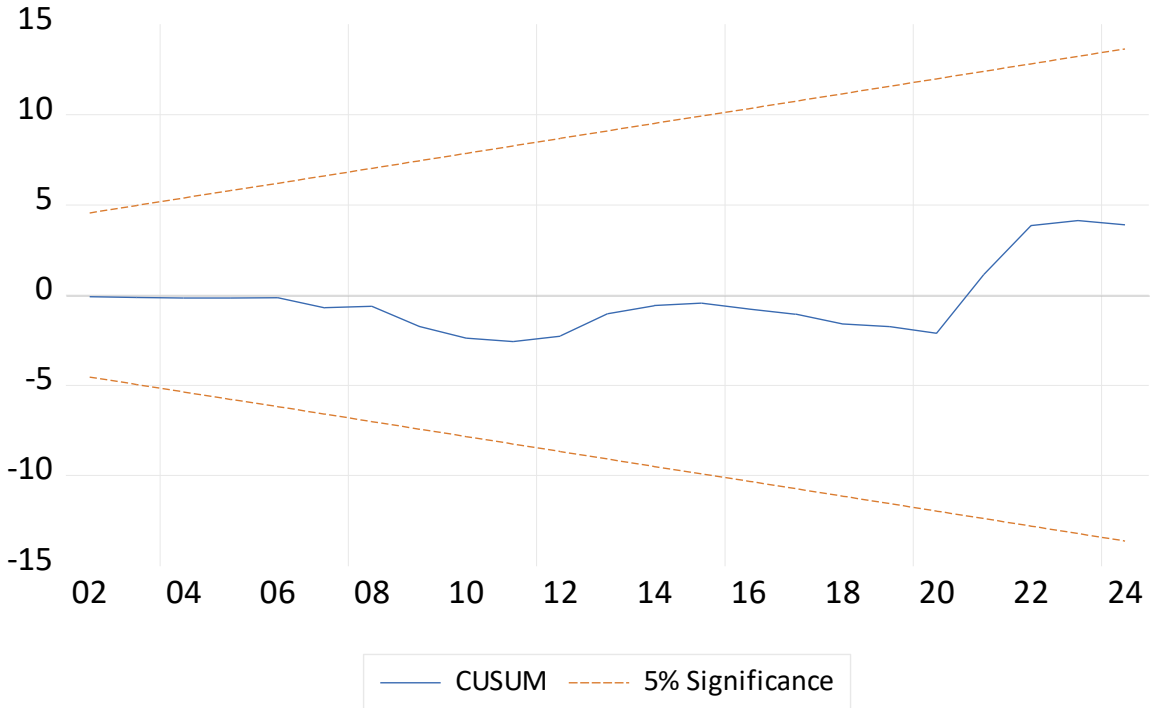
R^2 (R-squared) is 0.87. This number is higher than 0.7 means that income from transportation approximate expenditure to goods transportation is strong.

F-statistics is 154.8 and Prob(F-statistics) is 0 and this number is less than Prob(0.05) means that regression model parameters are important.

Income from transportation (Prob) is 0 and it is less than Prob(0.05) it means that parameter is important.

C (constant) Probability is 0.57 and it is more than Prob(0.05), it means that parameter is unimportant.

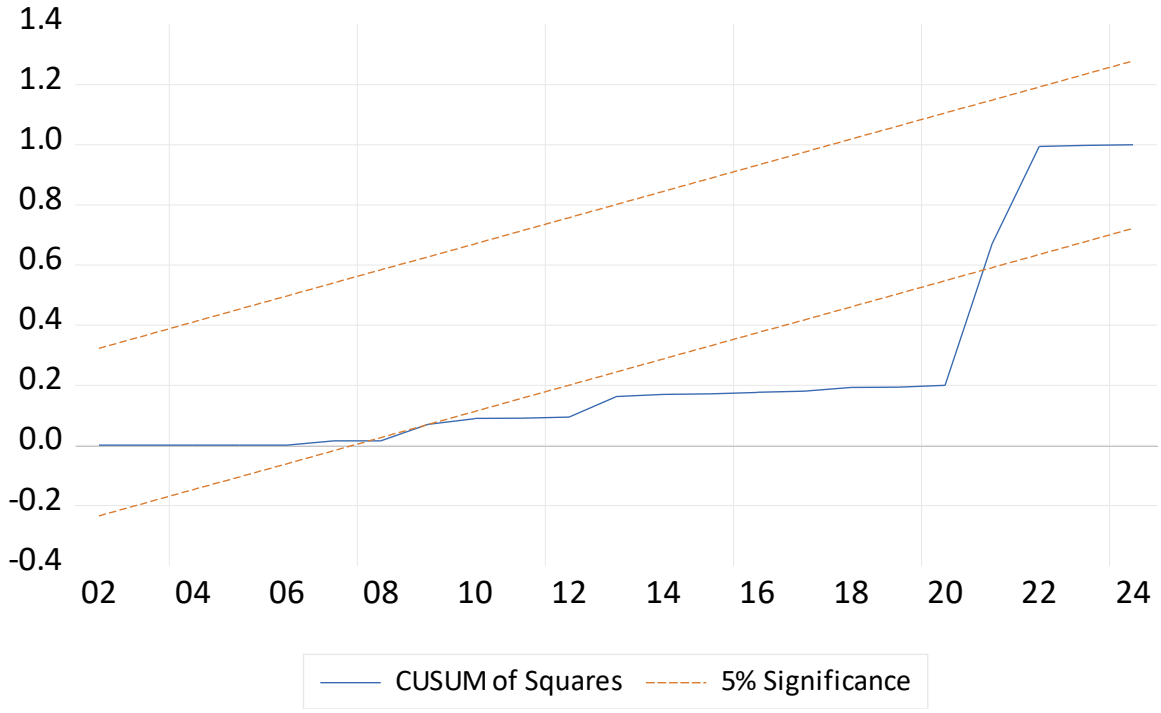
Durbin-Watson statistics is 1.04 and it is less than 2, it means that autocorrelation (regression model errors) is negative.



Graph 5. Result of CUSUM test

These tables show Cusum and Cusum square tests. They define stability between parameters.

In this graph, Blue line (main line) does not intersect with red lines (border lines), it means that regression model parameters are stable.



Graph 6. Result of CUSUM of Squares test

In this graph, Blue line (main line) intersects with red lines (border lines), it means that regression model parameters are unstable.

Table 6.

The result of White test

This graph shows homoscedasticity or heteroscedasticity of regression model errors with White test

Heteroskedasticity Test: White

Null hypothesis: Homoskedasticity

F-statistic	4.230743	Prob. F(2,22)	0.0279
Obs*R-squared	6.944413	Prob. Chi-Square(2)	0.0310
Scaled explained SS	7.289017	Prob. Chi-Square(2)	0.0261

F-statistic (Prob) is 0.0279 and this number is less than Prob(0.05) it means that regression model errors are heteroscedastic.

Table 7.

Result of Dickey-Fuller test

This graph presents stationary or non-stationary of time series.

Null Hypothesis: D(INCOME_FROM_TRANSPORTATION_IN_THE_TRANSPORT_SECTOR__THOUSAND_MANATS) has a unit root

Exogenous: None

Lag Length: 0 (Automatic - based on SIC, maxlag=5)

		t-Statistic	Prob.*
Augmented Dickey-Fuller test statistic		-2.965385	0.0049
Test critical values:	1% level	-2.669359	
	5% level	-1.956406	
	10% level	-1.608495	

In here, Dickey-Fuller t-statistic is (-2.97) and it is less than critical values (1%, 5%, 10%) and Dickey-Fuller t-statistic Prob (0.0049) is less than Prob(0.05), it means that time-series are stationary

Conclusion

Based on data analysis, the air travel sector in Azerbaijan has grown significantly in recent years. The data of the goods turnover from 1996 to 2024 are examined in this study. In the 1990s and early 2000s, the turnover of commodities was low; however, after 2013, it started to rise. Due to the development of logistics infrastructure, the construction of new international airports, and the revival of international trade after the pandemic, the biggest growth occurred between 2020 and 2024.

In this study, we examined the regression equation, importance of regression model, CUSUM test and heteroskedasticity tests. Results show that the regression model parameters are important and autocorrelation is positive. In CUSUM test, we have analyzed that regression model parameters are stable.

In conclusion, we can state that the turnover of goods in Azerbaijan's transportation industry has increased favorably. There are diminishing directions that are impacted by negative factors like COVID-19 or political events, even though there are fluctuations in the tables that result from positive factors like new projects (BTC, TAP, TANAP) and increasing energy consumption. It is obvious that Azerbaijan had a major impact on the global energy system, particularly for European nations, which benefited Azerbaijan's economic and political might.

This study examined the relationship between the turnover of goods and the expenditure of goods in maritime transport in Azerbaijan over the period 2001–2024 using a simple linear regression model and a set of econometric diagnostic tests. The empirical findings indicate that there is a statistically significant relationship between the variables, as confirmed by the F-statistic and t-statistic results ($p < 0.05$). The R^2 value of 0.367 suggests a moderate level of explanatory power, meaning that turnover of goods explains a noticeable portion of the variation in expenditure. However, despite statistical significance, the model reveals several important econometric limitations. The negative coefficient implies an inverse relationship between turnover and expenditure, which is not fully consistent with economic expectations and may indicate model misspecification or omitted variables. In addition, the Durbin–Watson statistic points to the presence of positive autocorrelation in the residuals, violating the classical regression assumptions. Furthermore, the results of the CUSUM and CUSUM of squares tests demonstrate that the model parameters are unstable over time, suggesting structural changes within the maritime transport sector. The White test confirms the presence of heteroscedasticity, indicating that the variance of the error terms is not constant and reducing the efficiency of the estimates. Overall, while the regression model is statistically significant, it does not provide a fully reliable representation of the economic relationship between turnover and expenditure in Azerbaijan's maritime transport sector. These findings suggest that more advanced econometric approaches, along with the inclusion of additional explanatory variables such as fuel costs, infrastructure development, and international trade conditions, are necessary to obtain more accurate and robust results. Despite these limitations, maritime transport continues to play a strategically important role in Azerbaijan's economy, particularly through its integration into regional and global trade corridors.

Overall, the study discusses the role of Azerbaijan in global energy market and mention about substantial role of these energy resources in economic growth of Azerbaijan. Also it describes role of infrastructure developments and investments to pipeline transportation and its effects to the income from pipeline transport. The country's strategic response to global events, such as the Russia-Ukraine war, has further reinforced its importance as a reliable energy supplier to Europe.

This research analyzed the development and economic role of pipeline transportation in Azerbaijan over 2000-2024 using econometrical analysis. The regression analysis revealed a strong and positive relationship between income from transportation and expenditure on goods transportation in the transport sector. With an R-squared value of 0.87, the model demonstrates a high explanatory power, indicating that changes in transportation income significantly influence expenditure levels. The statistical significance of the independent variable further supports the reliability of this relationship. Augmented Dickey-Fuller test confirms that the time series data is stationary, which strengthens the validity of the regression results. Nevertheless, future research could improve the model by addressing additional variables to capture broader economic dynamics.

References

1. Aysel Mammadova, Ruslan Najafov, Elvin Huseynov. "Descriptive and Correlation Analysis of Income, Spending, and Commodity Turnover in Azerbaijan's Transport Sector" International Research Journal of Economics and Management Studies, Vol. 4, No. 12, pp. 96-107, 2025. Crossref. http://doi.org/10.56472/25835238/IRJEMS-V4I12P112

2. Imamoglu, H., & Imanov, T. Analysis of commercial air transport impact on environmental degradation: Validity of Environmental Kuznets Curve hypothesis for Azerbaijan.

3. Niftiyev, I. (2024) 'Multidimensional assessment of transportation sector's performance: Non-parametric analysis of the Azerbaijani economy', St. Petersburg University Journal of Economic Studies, 40 (4), pp. 587–606. https://doi.org/10.21638/spbu05.2024.404

4. Alirzayev, E., & Huseynova, S. (2025). Empirical Evidence Of J-Curve Effect and Marshall Lerner Condition: Case of Azerbaijan. *The Scientific-Analytical Journal" Economic Reforms"*, *2025*(1), 40-56.

5. Huseynova, S., & Qurbanova, N. (2025). THE ROLE OF STATE POLICY IN REGULATING TRANSPORT AND LOGISTICS SERVICES IN THE DEVELOPMENT OF FOREIGN TRADE. *Sciences of Europe*, (162), 15-17.

6. Huseynova, S., & Kazimov, J. (2025). Investment Incentives as a Tool for Sustainable Economic Development in the Azerbaijan Republic. *International Research Journal of Economics and Management Studies IRJEMS*, *4*(11).

7. Huseynova S.M., Nwolisa N. Assessing the Impact of İnvestment and Oil Prices on the Trade Balance Between Azerbaijan and Russia Using Econometric Methods. *Statistics and Economics*. 2026;23(1):82-90. (In Russ.) https://doi.org/10.21686/2500-3925-2026-1-82-90

8. Huseynova Sara Mubariz (2016). The influence of international migration on international trade. European journal of economics and management sciences, (3), 27-29.

9. Hüseynova, S. Kapsayici Kalkinma Göstergelerinin Ekonomik Kalkinma Üzerindeki Etkisi. *Scientific Collection «InterConf+»*, (30), 28-31.

10. Huseynova, S., & Ch, I. Analysis of the WtO and the process of integration of Azerbaijan into the world economy summary. *Genetics and Biotechnology*, *25*.

11. Sara M. Huseynova, & Telman J. Hajizada (2024). Analysis of the Stability of the Banking Sector of Azerbaijan in Conditions of Economic Crisıs Based on the Econometric Model. Статистика и экономика, 21 (2), 35-49. doi: 10.21686/2500-3925-2024-2-35-49

12. Huseynova, S. (2023). Cointegration analysis of economic growth parameters between Russia and Azerbaijan. *Sciences of Europe*, (110), 26-31.

13. State Statistical Committee of the Republic of Azerbaijan. (1996–2024). Air transport turnover and income statistics.

14. International Air Transport Association (IATA). World Air Transport Statistics.

15. Alkaabi, K., & Debbage, K. (2011). "Air cargo, globalization and economic development." Journal of Air Transport Management, 17(5), 335–339.

16. Graham, A. (2018). Managing Airports: An International Perspective. Routledge.

17. United Nations Conference on Trade and Development. (Various years). Review of Maritime Transport. Geneva: UNCTAD.

18. State Statistical Committee of the Republic of Azerbaijan. (2024). Transport Statistics of Azerbaijan (2001–2024). Baku.

19. Yang, C.-C.. (2012). Assessing the moderating effect of innovation capability on the relationship between logistics service capability and firm performance for ocean freight forwarders. International Journal of Logistics Research and Applications, 15(1), 53–69.

20. Caliskan, Aylin, & Ozturkoglu, Yucel. (2016). Maritime logistics functions and their impact on operational efficiency. Journal of Transport and Supply Chain Management.

21. Volatility and Shock Transmission in Maritime Freight Rates: A SARIMAX-EGARCH Approach. (2023). Analysis of freight rate volatility using BDI and container indices.

22. Profiling Global Maritime Hubs: Statistical Characteristics of Port Types and Trade Corridors. (2025). Cluster analysis of global port performance and trade connectivity.

23. Dickey, David A., & Fuller, Wayne A.. (1979). Distribution of the estimators for autoregressive time series with a unit root. Journal of the American Statistical Association, 74(366), 427–431.

24. White, Halbert. (1980). A heteroskedasticity-consistent covariance matrix estimator and a direct test for heteroskedasticity. Econometrica, 48(4), 817–838.

25. Durbin, James, & Watson, Geoffrey S.. (1950). Testing for serial correlation in least squares regression. Biometrika, 37(3–4), 409–428.

26. Brown, R. L., Durbin, J., & Evans, J. M.. (1975). Techniques for testing the constancy of regression relationships over time. Journal of the Royal Statistical Society: Series B, 37(2), 149–192.

27. THE AGREEMENT OF THE CENTURY – AN INTERNATIONAL PROJECT THAT TURNS AZERBAIJAN INTO AN INTEGRAL PART OF THE GLOBAL WORLD ECONOMY (Huseynova Nurana, 2025)

28. State Statistical Committee of the Republic of Azerbaijan (2024) – Transport statistics of Azerbaijan (2000 – 2024)

29. IMPLICATIONS OF THE BAKU-TBILISI-CEYHAN MAIN OIL PIPELINE PROJECT (Tuncay Babalı, 2005)

30. The Policies around the BTC Pipeline – (Halil Erdemir, 2009)

31. OIL AND GAS PIPELINE STRATEGY OF A LANDLOCKED COUNTRY: CASE OF AZERBAIJAN – (Gorkhmaz Askerov, 2008)

32. AZERBAIJAN ENERGY STRATEGY AND THE IMPORTANCE OF THE DIVERCIFICATION OF EXPORTED TRANSPORT ROUTES – (Rovshan IBRAHIMOV, 2010)

33. UKRAINIAN WAR AND ITS IMPACT ON SOCIA-ECONOMIC SITUATION IN AZERBAIJAN – (Fidan Namazova, 2023)

34. The Economic Consequences of Russia-Ukraine War for Azerbaijan – (Emin Mammadov, 2022)

ЭФФЕКТИВНОСТЬ ПРОМЫШЛЕННЫХ КОРПОРАЦИЙ КАЗАХСТАНА В КОНТЕКСТЕ МЕЖДУНАРОДНОГО ОПЫТА

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EFFICIENCY OF INDUSTRIAL CORPORATIONS OF KAZAKHSTAN IN THE CONTEXT OF INTERNATIONAL EXPERIENCE

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АННОТАЦИЯ

В статье исследуется влияние структуры собственности на экономическую эффективность промышленных корпораций Республики Казахстан. На основе статистического анализа финансово-хозяйственных показателей деятельности предприятий выявлены ключевые проблемы управления собственностью в различных секторах экономики. В работе проведен сравнительный анализ моделей корпоративного управления Казахстана, Германии и Польши, что позволило определить наиболее устойчивые конфигурации владения и контроля. Особое внимание уделено количественной и качественной оценке эффекта от внедрения цифровых инструментов. Установлена прямая корреляция между уровнем профессиональной подготовки управленцев и результативностью использования активов. По итогам исследования предложена авторская модель трансформации системы управления, направленная на укрепление кадрового и организационного потенциала промышленных гигантов РК.

ABSTRACT

This article investigates the impact of ownership structure on the economic performance of industrial corporations in the Republic of Kazakhstan. Based on a statistical analysis of financial and operational indicators, the study identifies key challenges in property management across various economic sectors. A comparative analysis of corporate governance models in Kazakhstan, Germany, and Poland was conducted to determine the most resilient configurations of ownership and control. Particular attention is paid to the quantitative and qualitative assessment of the effects of digital tool implementation. A direct correlation between the level of professional management training and asset utilization efficiency is established. Based on the findings, the author proposes a transformation model for the management system aimed at strengthening the human and organizational capacity of industrial giants in Kazakhstan.

Ключевые слова: структура собственности, промышленные корпорации, эффективность управления, корпоративное управление, сравнительный анализ, цифровизация управления, человеческий капитал, промышленный сектор.

Keywords: ownership structure, industrial corporations, management performance, corporate governance, comparative analysis, digitalization of management, human capital, industrial sector.

В современной экономике Казахстана наблюдается критический разрыв между формальной структурой владения и фактической эффективностью использования промышленных активов. Основная проблема заключается в инертности существующих механизмов управления собственностью, которые не обеспечивают должной доходности и рыночной гибкости предприятий [1]. Высокая концентрация государственного участия в стратегических секторах в сочетании с медленной адаптацией международного опыта корпоративного управления (в частности, моделей Германии и Польши) препятствует качественному росту промышленного потенциала. Ситуация усугубляется фрагментарным внедрением цифровых инструментов мониторинга активов и острым дефицитом квалифицированных управленческих кадров, способных работать в условиях глобальной конкуренции. Без системной трансформации моделей владения, глубокой цифровизации процессов и качественного

апгрейда кадрового потенциала невозможно достижение целевых показателей эффективности и устойчивого развития индустриального сектора Республики Казахстан.

Анализ последних исследований свидетельствует о растущем интересе научного сообщества к поиску оптимального баланса между государственным участием и рыночными механизмами в управлении промышленным сектором. Современные авторы, рассматривая опыт трансформационных экономик, подчеркивают, что жесткие структуры собственности в Казахстане постепенно сталкиваются с необходимостью адаптации к стандартам ОЭСР, что находит отражение в работах, посвященных децентрализации контроля и внедрению принципов транспарентности. В международных публикациях последних лет, анализирующих модели Германии и Польши, акцент смещается в сторону институциональной независимости менеджмента и роли стратегических инвесторов в повышении эффективности активов. Параллельно с этим, в свежих исследованиях по цифровой экономике обосновывается критическая значимость внедрения систем управления данными (Big Data и ERP) для повышения прозрачности корпоративного сектора. Также эксперты всё чаще связывают результативность управления не столько с формой владения, сколько с качеством человеческого капитала, указывая на прямую зависимость между профессионализацией управленческих кадров и инвестиционной привлекательностью промышленных корпораций в условиях глобальной нестабильности [2].

Несмотря на наличие фундаментальных исследований в области корпоративного управления, вне поля зрения ученых остается вопрос адаптации классических европейских моделей владения к специфическим институциональным условиям промышленного сектора Казахстана. В частности, недостаточно изученным является механизм прямой интеграции цифровых аналитических инструментов в процессы принятия решений по управлению собственностью, а также отсутствует комплексная оценка синергетического эффекта от одновременного внедрения ИТ-решений и повышения квалификации управленческого состава [3]. Кроме того, в современной литературе слабо представлены прикладные алгоритмы перехода от текущих инертных структур управления к гибким целевым моделям, которые учитывали бы отраслевую специфику казахстанской промышленности. Остается нераскрытым и вопрос разработки дифференцированных мер повышения эффективности управления активами в зависимости от доли участия государства, что создает методологический пробел в формировании стратегий долгосрочного развития промышленных корпораций РК в условиях цифровой трансформации.

Целью статьи является обоснование научно-методических подходов и разработка практических рекомендаций по повышению эффективности управления собственностью промышленных корпораций Республики Казахстан на основе сравнительного анализа международного опыта и внедрения цифровых инструментов. Для достижения этой цели в работе решаются задачи по выявлению системных проблем в управлении активами, проведению сравнительного анализа моделей корпоративного управления Казахстана, Германии и Польши, а также оценке влияния профессиональных компетенций и цифровизации на результативность деятельности предприятий. Итогом исследования выступает формирование целевой модели управления и комплекса мер по укреплению кадрового и организационного потенциала промышленного сектора страны [4].

Управление собственностью в промышленных корпорациях представляет собой ключевой компонент системы корпоративного управления, от которого зависят эффективность использования активов, инвестиционная привлекательность и устойчивость бизнеса. В Республике Казахстан развитие механизма управления собственностью осуществляется в рамках реализации программ приватизации, реформирования квазигосударственного сектора экономики и активного привлечения иностранного капитала.

С позиции институциональной теории собственность определяется как совокупность формализованных прав владения, пользования и распоряжения активами. В свою очередь, механизм управления собственностью представляет собой систему органов и процедур, направленных на обеспечение эффективной реализации этих прав.

Для анализа текущего состояния механизмов управления собственностью в промышленных корпорациях Казахстана целесообразно рассмотреть данные по ведущим предприятиям обрабатывающей промышленности. В частности, структура собственности крупных промышленных корпораций демонстрирует высокую долю участия квазигосударственного сектора. По данным Комитета по статистике Агентства по стратегическому планированию и реформам Республики Казахстан (2025 г.), значительная часть крупных промышленных предприятий принадлежит компаниям, входящим в структуру акционерного общества «Самрук-Қазына».

Таблица 1

Основные формы собственности промышленных предприятий РК (на 2024-2025гг)

Форма собственности	Количество предприятий	Доля от общего числа, %
Государственная (в т.ч. Самрук-Қазына)	512,14	1,4
Частная казахстанская	32 186	85,1
Иностранная	1 654	4,4
Совместная (смешанная)	3 428	9,1
Всего	**37 780**	**100**
Примечание: составлено автором на основе источника [5]		

Анализ представленных статистических данных позволяет отметить, что доля государственных корпораций в промышленном секторе Казахстана по-прежнему остаётся значительной. В то же время наблюдается устойчивая тенденция к сокращению степени прямого государственного участия и усилению роли частных инвесторов, включая иностранных. Эти изменения оказывают существенное влияние на трансформацию механизмов корпоративного управления, способствуя их адаптации к рыночным условиям и международным стандартам.

Несмотря на количественное преобладание предприятий с формой частной собственности, государственный сектор сохраняет весомую долю в стратегически значимых отраслях, таких как металлургия, переработка нефти, транспортное машиностроение и электроэнергетика. Участие государства в этих секторах обусловлено необходимостью обеспечения национальной безопасности, устойчивого экономического развития и контроля над ключевыми ресурсами [6].

Корпорации с участием государства функционируют в рамках специализированной модели корпоративного управления, регламентированной внутренними нормативными документами холдинга АО «Самрук-Қазына». В соответствии с действующей редакцией Кодекса корпоративного управления фонда (2021 г.), система управления включает следующие ключевые органы:

– Общее собрание акционеров;
– Совет директоров;
– Правление;

Комитеты при Совете директоров (в том числе по аудиту, стратегическому планированию, вознаграждениям и другим направлениям).

Эта модель направлена на повышение прозрачности управления, усиление подотчётности и внедрение лучших практик корпоративного регулирования в государственном секторе экономики [7].

Таблица 2

Структура собственности и управления в отдельных промышленных корпорациях РК (2025 г.)

Наименование корпорации	Форма собственности	Доля участия государства, %	Наличие независимых директоров	Применение ESG-стандартов
АО «НК «КазМунайГаз»	Смешанная (Public)	~90	4 из 9 (усиление состава)	Рейтинг «A-» (Low Risk)
АО «Qarmet»	Частная казахстанская	0	Формирование пула (3+)	Экологическая модернизация
АО «НАК «Казатомпром»	Смешанная (LSE/AIX)	75	3 из 7	Лидер (Net Zero Strategy)
АО «НК «Қазақстан темір жолы»	Государственная	100	4 из 9	Цифровой ESG-мониторинг
Eurasian Resources Group (ERG)	Смешанная	40	3 из 8	Декарбонизация активов
Примечание: составлено автором на основе источника [8]				

Данные 2025 года подтверждают тренд на профессионализацию менеджмента: в советах директоров национальных компаний доля независимых директоров с международным опытом достигла целевых 30-40%. Это позволило снизить коррупционные риски и повысить инвестиционный рейтинг казахстанского промышленного сектора на международной арене [9].

Эффективное управление собственностью представляет собой один из ключевых факторов устойчивого функционирования и стратегического развития предприятий в условиях рыночной экономики. В Республике Казахстан, несмотря на наличие нормативно-правовой базы, регулирующей имущественные отношения, сохраняется ряд структурных и институциональных проблем, сдерживающих полноценную реализацию потенциала собственности как экономического ресурса.

Во-первых, наблюдается низкий уровень институциональной прозрачности в части регистрации, учёта и оборота имущества, особенно в секторе малого и среднего бизнеса. Сложности при оформлении прав собственности, несовершенство кадастровой и регистрирующей систем затрудняют

инвестиционную активность, в том числе со стороны иностранных и частных инвесторов.

Во-вторых, характерной проблемой остаётся недостаточная эффективность корпоративного управления в компаниях с долей государства или с широкой диверсификацией собственников. Часто отсутствуют чётко определённые механизмы распределения прав и ответственности между владельцами, наблюдательными советами и исполнительными органами, что порождает конфликты интересов и снижает оперативность принятия решений.

В-третьих, в Казахстане наблюдается концентрация собственности в руках ограниченного круга лиц, что приводит к слабой конкуренции и ограниченному доступу к ключевым активам для новых участников рынка. Это затрудняет развитие предпринимательства и инновационной активности в стратегически важных отраслях, включая инфраструктурное строительство.

Кроме того, остаётся нерешённым вопрос оценки и эффективного использования государственной и муниципальной собственности. Многие объекты, находящиеся на балансе государства, используются неэффективно или простаивают, что требует модернизации механизмов передачи их в доверительное управление, аренду или приватизацию с привлечением частного капитала.

Также стоит отметить недостаток квалифицированных специалистов в сфере управления собственностью, особенно на региональном уровне. Это снижает качество принятия управленческих решений в области распоряжения активами и их трансформации под потребности текущего и долгосрочного развития бизнеса.

Таблица 3.

Основные проблемы управления собственностью в Казахстане по секторам экономики

Сектор экономики	Характерные проблемы	Возможные последствия
Государственный сектор	Низкая эффективность использования имущества; устаревшая инвентаризация активов	Потери бюджета, дублирование функций
Малый и средний бизнес (МСБ)	Трудности регистрации прав, слабая защита собственности	Ограничение доступа к кредитам и инвестициям
Корпоративный сектор	Конфликт интересов между акционерами и менеджментом; непрозрачность владения	Ухудшение инвестиционного климата
Строительно-инфраструктурная отрасль	Несовершенство землеустройства; проблемы с выделением участков	Задержки реализации проектов, рост затрат
Аграрный сектор	Неоформленные или устаревшие права на землю; слабый кадастр	Низкая производительность, проблемы с залогом
Примечание: составлено автором на основе источника [10]		

Таким образом, проблемные аспекты управления собственностью в Казахстане обусловлены совокупностью правовых, институциональных и кадровых ограничений. Для их преодоления необходим системный подход, включающий модернизацию законодательства, цифровизацию кадастровых и регистрирующих систем, развитие корпоративной культуры, а также формирование кадрового потенциала в данной сфере

В современных условиях эффективное управление собственностью выступает одним из ключевых факторов повышения конкурентоспособности предприятий и устойчивости экономики в целом. В Казахстане данный механизм сталкивается с рядом вызовов, включая фрагментированность нормативно-правовой базы, недостаточную прозрачность процессов распоряжения активами, а также слабую институциональную поддержку в вопросах оценки и инвентаризации имущества. Для преодоления указанных проблем необходима поэтапная модернизация существующих подходов [11].

Во-первых, следует обеспечить цифровизацию системы учёта и управления имущественными правами, что возможно через развитие Единого государственного реестра имущества и внедрение блокчейн-технологий для повышения прозрачности сделок. Во-вторых, важно усилить ответственность и компетенции органов корпоративного управления, особенно в сфере государственной собственности, где актуальны вопросы неэффективного использования активов.

Кроме того, необходимо создать независимые экспертные центры по оценке и мониторингу активов с участием представителей академического сообщества, бизнеса и государственных структур. В части малого и среднего бизнеса следует расширить доступ к программам по правовой защите собственности и финансированию под залог имущества, особенно в сельской местности и на периферии.

Для повышения эффективности механизма управления собственностью предлагается реализация мер, представленных на рисунке 1.

Комплексное совершенствование механизма управления собственностью в Казахстане требует системного подхода, сочетающего институциональные реформы, технологические инновации и развитие человеческого капитала, способного реализовать современные принципы управления имущественными комплексами в условиях рыночной трансформации.

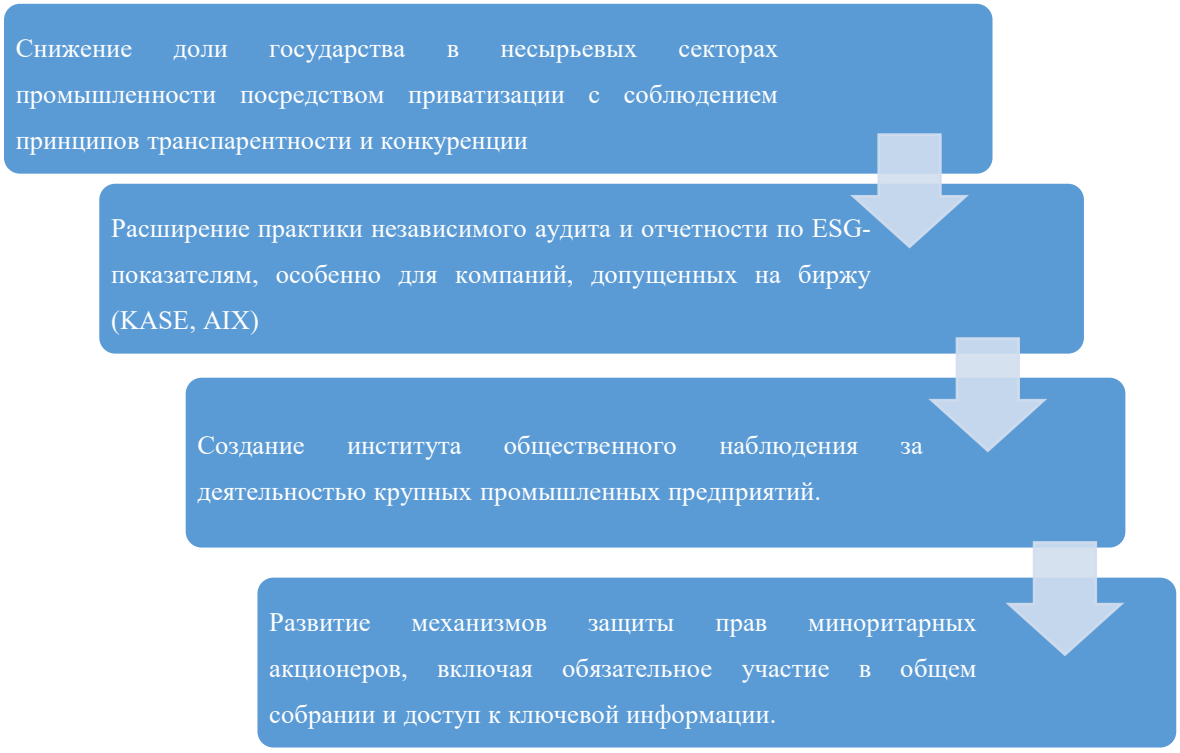
Снижение доли государства в несырьевых секторах промышленности посредством приватизации с соблюдением принципов транспарентности и конкуренции
Расширение практики независимого аудита и отчетности по ESG-показателям, особенно для компаний, допущенных на биржу (KASE, AIX)
Создание института общественного наблюдения за деятельностью крупных промышленных предприятий.
Развитие механизмов защиты прав миноритарных акционеров, включая обязательное участие в общем собрании и доступ к ключевой информации.

Рисунок 1 – Меры повышения эффективности механизма управления собственностью
Примечание: Составлено автором на основе источника [12].

Таким образом, проблемные аспекты управления собственностью в Казахстане обусловлены совокупностью правовых, институциональных и кадровых ограничений. Для их преодоления необходим системный подход, включающий модернизацию законодательства, цифровизацию кадастровых и регистрирующих систем, развитие корпоративной культуры, а также формирование кадрового потенциала в данной сфереТаким образом, механизм управления собственностью в промышленных корпорациях Казахстана продолжает находиться в зависимости от государственного участия. Однако в последние годы наметились позитивные изменения, выражающиеся в укреплении стандартов корпоративного управления, расширении прозрачности и привлечении независимых экспертов в органы управления. Дальнейшее совершенствование данного механизма требует как институциональных преобразований, так и практической реализации принципов добросовестности, устойчивости и подотчётности.

В целях повышения эффективности и устойчивости промышленного сектора нами предлагаются комплекс рекомендаций по совершенствованию управления собственностью, представленная в таблице

На наш взгляд, потенциальный эффект от реализации вышеуказанных мер позволит:

– повысить инвестиционную привлекательность корпораций,

– увеличить доходность управления активами за счёт оптимизации портфеля,

– снизить уровень административной нагрузки,

– ускорить переход к модели устойчивого роста.

Таблица 11

Рекомендации по совершенствованию управления собственностью

№	Направление изменений	Конкретные меры	Ожидаемый эффект
1	Институциональное развитие	Внедрение независимых советов директоров	Повышение прозрачности и контроля
2.	Диверсификация активов	Расширение участия в высокотехнологичных отраслях	Снижение рисков и повышение доходности
3.	Оценка эффективности управления	Введение KPI для топ-менеджмента, привязанных к рыночным метрикам	Мотивация к результативному управлению
4.	Прозрачность	Публикация отчётов о доходности активов и инвестициях	Повышение доверия инвесторов
5.	Взаимодействие с рынками капитала	Листинг на фондовых рынках, выпуск корпоративных облигаций	Расширение инвестиционной базы
Примечание: составлено автором на основе источника []			

В таблице 12 обобщены ключевые характеристики существующей модели управления и предлагаемого подхода, что позволяет провести их сопоставительный анализ.

Таблица 12

Сравнение текущей и рекомендованной моделей управления

Показатель	Текущая модель	Рекомендованная модель
Прозрачность	Средняя	Высокая
Эффективность управления	Ограниченная	Повышенная через KPI и аудит
Участие частных инвесторов	Ограниченное	Активное
Адаптивность	Низкая	Гибкая, реагирующая на рынок
Примечание: составлено автором		

Анализ данных таблицы 12 позволяет выявить ключевые различия между текущей и рекомендуемой моделями управления. Текущая система характеризуется фрагментарностью управленческих процессов, недостаточной координацией между структурными подразделениями, а также отсутствием гибких механизмов адаптации к изменениям внешней среды. В свою очередь, предложенная модель ориентирована на интеграцию функций управления, усиление стратегического планирования и внедрение современных инструментов контроля и мотивации.

Одним из существенных отличий является переход от преимущественно административного стиля управления к более современному подходу, основанному на принципах результативности, прозрачности и вовлечённости персонала. Это позволяет не только повысить эффективность внутренних процессов, но и способствует формированию устойчивой корпоративной культуры.

Также стоит отметить усиление роли аналитических инструментов в предлагаемой модели, что отражает тенденцию к цифровизации управления и принятию решений на основе объективных данных. Такая трансформация предполагает необходимость повышения квалификации управленческого персонала и внедрения новых технологий.

Таким образом, представленное сравнение подчёркивает значительный потенциал рекомендованной модели в части повышения общей эффективности управления, стратегической устойчивости и конкурентоспособности организации в долгосрочной перспективе.

Современные вызовы, стоящие перед промышленными корпорациями Казахстана, требуют пересмотра действующих подходов к управлению собственностью с учётом мировых тенденций и технологических изменений. Ниже представлены рекомендации, направленные на повышение эффективности данного механизма.

В первую очередь, это адаптация зарубежного опыта. Так, мировая практика демонстрирует, что устойчивые корпорации эффективно используют смешанные модели собственности и институциональные механизмы защиты прав акционеров, представлены в таблице 13.

Казахстанским корпорациям целесообразно внедрить модели корпоративного управления, основанные на принципах OECD (в частности, прозрачность собственности, защита миноритарных акционеров, стратегическое участие совета директоров).

Таблица 13

Сравнение моделей корпоративного управления (Казахстан – Германия – Польша)

Параметр	Казахстан	Германия	Польша
Структура собственности	Смешанная: государственные, частные и иностранные инвесторы	Преобладание институциональных инвесторов, значительная доля семейного капитала	Смешанная, усиливается роль частных и институциональных инвесторов
Роль государства	Существенная, особенно в стратегических отраслях	Ограниченная, в основном регулирующая функция	Умеренная, в переходный период играло активную роль
Защита прав инвесторов	Ограниченная защита миноритарных акционеров, слаборазвитая судебная практика	Высокая защита, чётко действующие правовые механизмы	Умеренная защита, постепенно усиливается в рамках требований ЕС
Механизмы управления	Одноуровневая система (совет директоров совмещает контроль и исполнение)	Двухуровневая система: наблюдательный совет и правление	Одноуровневая модель, но с элементами независимого контроля
Прозрачность и отчётность	Частично соблюдаются требования, недостаточная открытость корпоративной информации	Высокий уровень прозрачности, обязательный аудит, раскрытие информации	Улучшается с интеграцией европейских норм, растущая прозрачность

Роль независимых директоров	Формально закреплена, но фактическое влияние ограничено	Существенная роль, ключевые решения проходят через независимых членов	Расширяется, но уровень независимости остаётся ниже, чем в Германии
Уровень вовлечённости акционеров	Низкий, особенно со стороны миноритариев	Высокий, активно используется право голоса на собраниях	Средний, развивается культура корпоративного участия
Примечание: составлено автором на основе источника [13]			

Также можно перейти к двухуровневой системе управления (наблюдательный совет + исполнительный орган), как это реализовано в Германии и Нидерландах.

Кроме того, рекомендуется использовать опыт приватизационных моделей восточной европы, предусматривающих публичную отчётность и обязательную независимую оценку активов при смене собственника.

Во-вторых, интеграция цифровых и инновационных методов управления, поскольку современные технологии позволяют повысить прозрачность, эффективность и адаптивность механизмов управления собственностью.

Для этого рекомендуем внедрять цифровые платформы для мониторинга использования активов, включая блокчейн для фиксации прав собственности и транзакций с активами (рис. 10)

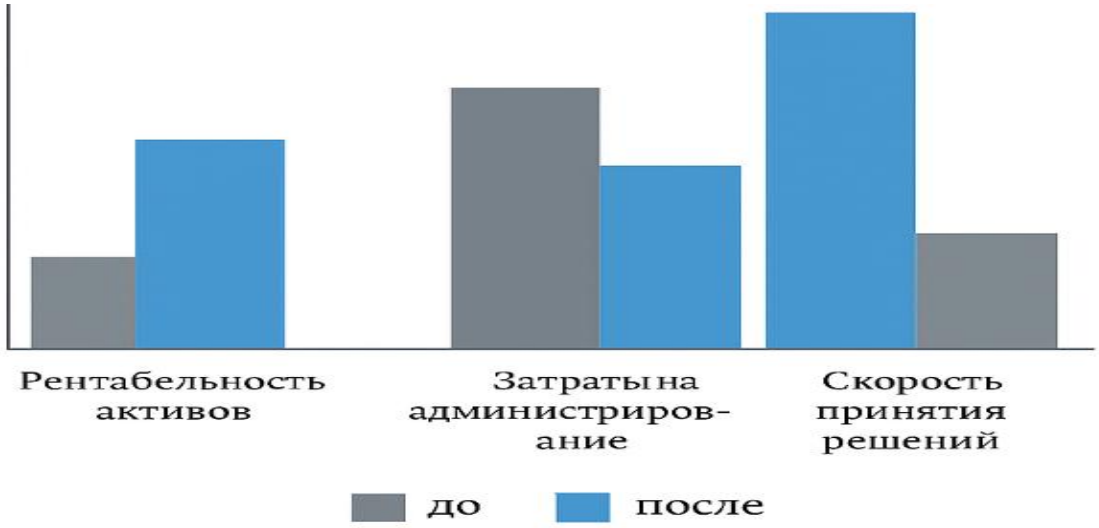

Рис. 10 – Эффект от внедрения цифровых инструментов в управлении корпоративной собственностью
Примечание: составлено автором на основе источника [9]

На диаграмме представлены сравнительные показатели до и после внедрения цифровых инструментов в управлении корпоративной собственностью. Видно, что рентабельность активов после цифровизации значительно возросла, что свидетельствует об оптимизации использования имущественного комплекса и повышении операционной эффективности.

Значительное снижение административных затрат отражает уменьшение издержек, связанных с документооборотом, контролем и мониторингом активов, что стало возможным благодаря автоматизации процессов. Наконец, увеличение скорости принятия решений демонстрирует рост адаптивности и управленческой мобильности предприятия, обусловленный внедрением аналитических платформ и инструментов цифрового взаимодействия между уровнями управления.

Эти данные подтверждаются исследованиями, показывающими, что компании, внедрившие цифровые технологии, добиваются значительного улучшения ключевых показателей эффективности.

Таким образом, внедрение цифровых решений оказывает комплексное положительное воздействие на систему управления собственностью, повышая её результативность и стратегическую устойчивость.

Также применять Big Data и искусственный интеллект для оценки эффективности использования собственности, прогнозирования доходности и выявления неэффективных управленческих решений.

Можно развивать цифровую паспортизацию активов и автоматизированные системы учёта нематериальных активов (например, прав на технологии и лицензии).

В третью очередь, совершенствование институциональной среды, для продолжения развития правовой базы и надзорных институтов, которая включает:

– уточнение юридических норм, регулирующих разделение функций владения и управления.

– расширение полномочий независимых директоров и наблюдательных советов.

Таблица 14

Сравнительный анализ эффективности управления собственностью в зависимости от уровня профессиональной подготовки управленцев

Страна / Регион	Уровень подготовки управленцев	Рентабельность активов (ROA), %	Ошибки в учёте и управлении имуществом (кол-во в год)	Средний срок принятия управленческого решения, дней
Казахстан (средний уровень)	Базовое экономическое или техническое образование	4,5%	12	18
Казахстан (высокий уровень)	MBA, сертификация по корпоративному управлению	7,2%	5	9
Германия	Профильное бизнес-образование + практика в советах директоров	9,5%	3	6
Польша	Обязательная переподготовка управленцев компаний	8,1%	4	7
Примечание: составлено автором на основе источника [10]				

– создание национального регистра собственности крупных промышленных объектов с публичным доступом для инвесторов и регуляторов.

Следовательно, на основе таблицы 14 уровень подготовки напрямую коррелирует с ростом рентабельности активов: высококвалифицированные управленцы эффективнее распоряжаются корпоративной собственностью. Количество ошибок в управлении существенно снижается при наличии профильного образования и сертификаций.

А скорость управленческих решений выше в странах с налаженными системами корпоративного образования и институционального контроля.

В четвертую очередь, укрепление кадрового и организационного потенциала, так как механизмы собственности не могут быть эффективными без квалифицированного управленческого состава.

Укрепление кадрового и организационного потенциала промышленных корпораций Казахстана является ключевым фактором повышения эффективности управления корпоративной собственностью. Реализация программ профессиональной подготовки и переподготовки, включая дуальное обучение и наставничество, способствует формированию высококвалифицированных специалистов, способных адаптироваться к современным требованиям производства [14]. В этой связи, рекомендуем разрабатывать направления, представленные на рисунке 11.

Внедрение инновационных методов управления и цифровых технологий требует от управленцев новых компетенций, что подчеркивает необходимость постоянного обновления знаний и навыков. Таким образом, системный подход к развитию человеческого капитала обеспечивает устойчивость и конкурентоспособность промышленных предприятий в условиях динамично меняющейся экономической среды.

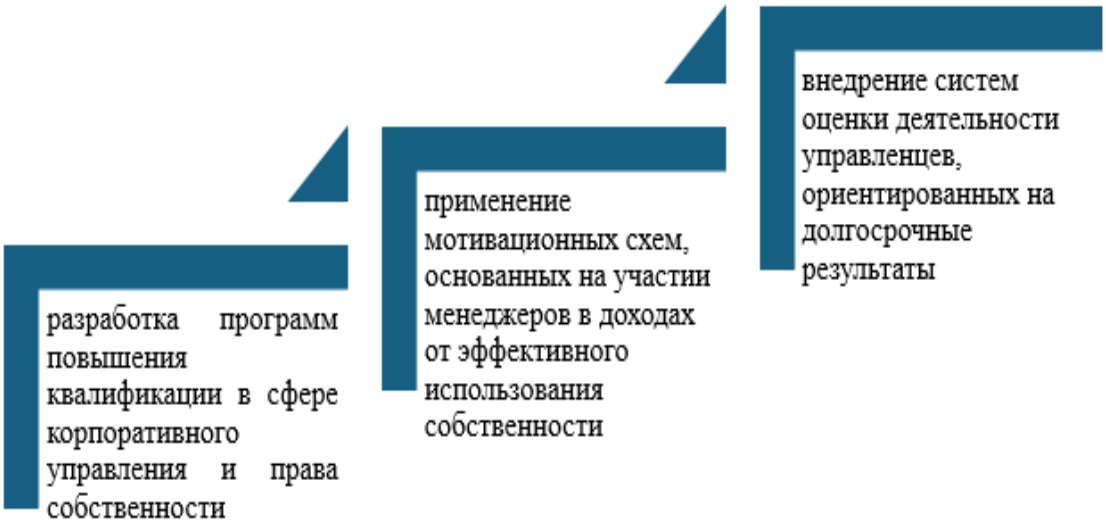
разработка программ повышения квалификации в сфере корпоративного управления и права собственности
применение мотивационных схем, основанных на участии менеджеров в доходах от эффективного использования собственности
внедрение систем оценки деятельности управленцев, ориентированных на долгосрочные результаты

Рис. 10 – Рекомендации по укреплению кадрового и организационного потенциала
Примечание: составлено автором

Подводя итог, следует констатировать, что в ходе исследования системы управления собственностью в промышленных корпорациях, проведенного на примере АО «НК «КазМунайГаз», обоснована необходимость трансформации существующих механизмов в сторону повышения прозрачности, экономической целесообразности и стратегической согласованности. Сформулированные рекомендации по оптимизации структуры владения, диверсификации активов и внедрению высокотехнологичных решений представляют собой прикладной инструмент, направленный на качественное улучшение управления активами и повышение прибыльности бизнеса.

Установлено, что совершенствование данного механизма требует системного подхода, включающего институциональные реформы, правовую модернизацию, глубокую цифровизацию процессов и непрерывное повышение квалификации кадров. Комплексная реализация предложенных мер позволит не только укрепить финансовую устойчивость национальных компаний, но и создать условия для роста их инвестиционной привлекательности и конкурентоспособности на глобальном уровне.

Литература

1. Berle, A. A., & Means, G. C. (1932/Modern Edition). The Modern Corporation and Private Property. (Классика теории: база для анализа структуры собственности).

2. OECD (2021). OECD Guidelines on Corporate Governance of State-Owned Enterprises. Paris: OECD Publishing. (Международный стандарт для анализа госсектора).

3. Abdimomunova, A., & Raissov, K. (2023). *Corporate Governance and Performance of State-Owned Enterprises in Kazakhstan.* Central Asian Economic Review, 5(2), 45-58. (Анализ эффективности госсектора РК).

4. Kozlowski, W., & Schmidt, M. (2020). Comparative Analysis of Corporate Governance Models: The Cases of Poland and Germany. European Management Review

5. Бюро национальной статистики АСПиР РК (2023). Основные показатели работы промышленных предприятий Республики Казахстан: Статистический сборник. Астана.

6. Nurlanova, N. K. (2022). Structural Transformation of Kazakhstan's Economy: Challenges and Priorities for Industrial Development. Central Asian Economic Review.

7. Указ Президента Республики Казахстан (2021). О Национальном плане развития Республики Казахстан до 2025 года.

8. Бюро национальной статистики АСПиР РК (2024). Промышленность Казахстана и показатели эффективности собственности: Статистический ежегодник. Астана.

9. Alibekova, G., & Tleubayev, A. (2022). *Digital Transformation of Kazakhstan's Industrial Sector: Challenges for Management.* Journal of Applied Economics and Business Research, 12(1), 15-30

10. Mutanov, G., & Mamyrov, N. (2023). Human Capital and Professional Competencies in Corporate Management: Evidence from Kazakhstan. International Journal of Human Resource Management, 34(4), 112-129

11. Закон Республики Казахстан (2015). О государственном имуществе (с изменениями и дополнениями по состоянию на 2026 г.). (Нормативная база РК).

12. Sabyrova, M. S. (2024). Digital Ecosystems in Corporate Property Management: A Case of Kazakhstan's Industrial Giants. Digital Science & Technology Review, 7(1), 44-56

13. World Bank (2022). Kazakhstan Digital Economy Assessment. Washington, DC: World Bank

14. Zheng, P., & Casanova, L. (2018). Digital Transformation in Large Corporations: Impact on Operational Efficiency. International Journal of Production Economics.

MEDICAL SCIENCES

BENIGN MULTICYSTIC PERITONEAL MESOTHELIOMA

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ABSTRACT

Benign multicystic mesothelioma of the peritoneum is a rare benign tumor that, unlike pleural mesothelial neoplasms, is not associated with asbestos exposure. The etiology and pathogenesis of multicystic peritoneal mesothelioma are unclear, although associations with some inflammatory and other pathological processes have been established. The diagnosis of this tumor is postoperative because it requires morphological verification due to the multiple cystic formations in the abdominal cavity with a similar macroscopic appearance.

We present a case of peritoneal localization of benign multicystic mesothelioma in a 79-year-old patient. The tumor measured 8/4/3 cm and was attached to the serosa of the small intestine. Its clinical manifestation was in the form of ileus, which necessitated urgent surgical intervention with removal of the formation.

The most common differential diagnostic options for similar cystic processes in the abdominal cavity are discussed, as well as the grounds for making this diagnosis from a morphological and biological point of view, despite the WHO recommendations for changing the nomenclature.

Keywords: benign multicystic peritoneal mesothelioma, peritoneal inclusion cyst, echinococcal cyst, pneumatosis cystoides intestinalis.

Introduction

Benign cystic mesothelioma, also called multicystic mesothelioma, is a rare tumor that is difficult to diagnose preoperatively, is more common in women, and is not associated with asbestosis, unlike mesothelial lesions of the pleura. Macroscopically, the tumor presents as a single-chamber or multi-chamber cyst, with smooth walls lined with mesothelial cells. Its cavity is filled with translucent fluid. The sizes of cystic mesotheliomas vary from 0.1 cm in diameter to over 30 cm in multi-chamber cystic formations [7, 8].

The pathogenesis of this benign tumor process is unclear. Various inflammatory and neoplastic factors are discussed for its occurrence. In women, it is often associated with endometriosis and inflammatory processes in the pelvic organs. WHO recommends the terminology peritoneal inclusion cysts instead of benign (multi) cystic mesothelioma. According to ICD-10 coding, the nomenclature of the process is Benign neoplasm of mesothelial tissue of peritoneum.

Case report

From the anamnesis: A 79-year-old man was admitted to the Surgical Department of Devin Hospital with severe abdominal pain and bloating, persistent vomiting, lack of gas and defecation for one day.

Clinical data: Due to the established clinical symptoms of intestinal obstruction (ileus), an exploratory laparotomy was performed. Intraoperatively, a multi-chamber cystic formation measuring 8/4/3 cm was found. It has a smooth, large-lobulated outer surface, soft-elastic consistency, fused with the serosa of the jejunum (Fig.1). In order to preserve the integrity of the intestinal wall, also considering the benign cystic appearance of the formation, as well as the patient's chronic concomitant diseases, a sparing partial excision of the pathological process was performed. The material was sent for biopsy examination.

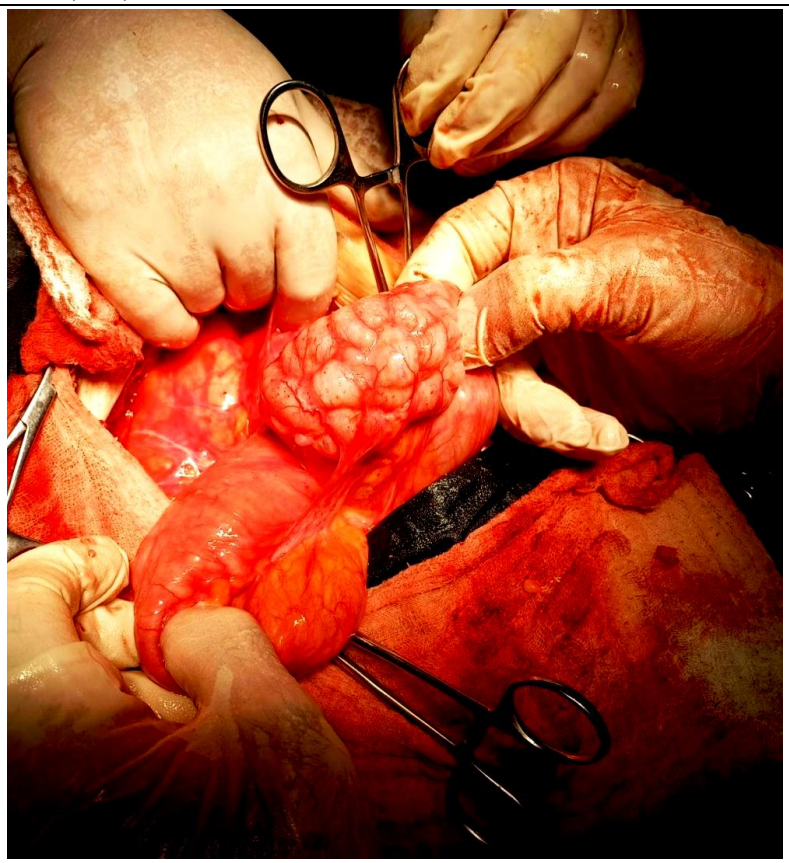

Fig. 1. Multicystic formation attached to the wall of a small intestinal loop

Material and methods

The histological specimens were made with fixative in 10% neutral formaldehyde (formalin) and embedded in paraffin. Sections were made with a thickness of 4 μm and stained with Hematoxylin and Eosin (HE).

Results of microscopic examination

Fragments of fibrous wall of a multi-chamber cyst lined by benign mesothelial cells (Fig.2). It occurs in areas with mesothelial proliferations. The morphological finding is consistent with benign multicystic peritoneal mesothelioma (peritoneal mesothelial inclusion cyst). According to WHO guidelines, a complete resection is recommended.

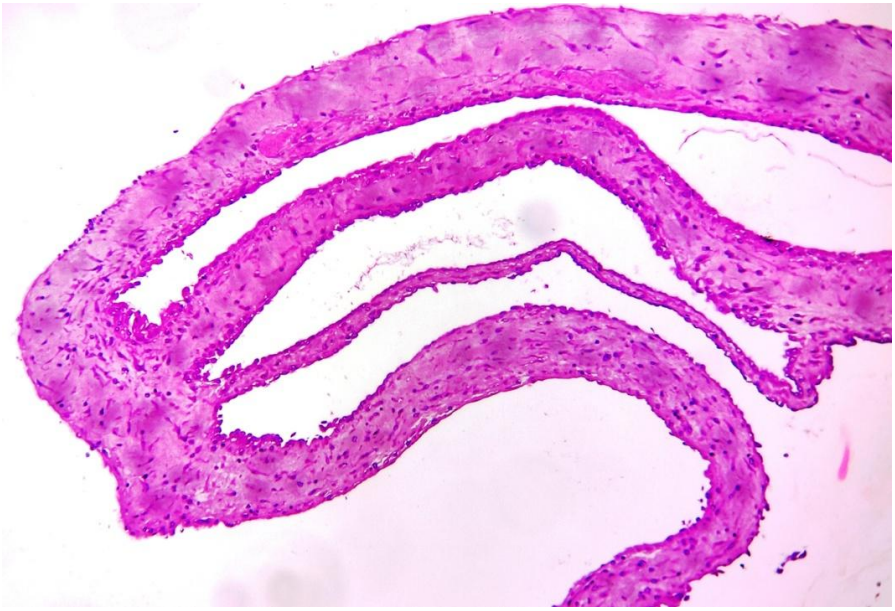

Fig. 2. Fibrous wall of a multi-chamber cystic formation, lined mainly by single-layer mesothelium, stained with HE, magn. X 100.

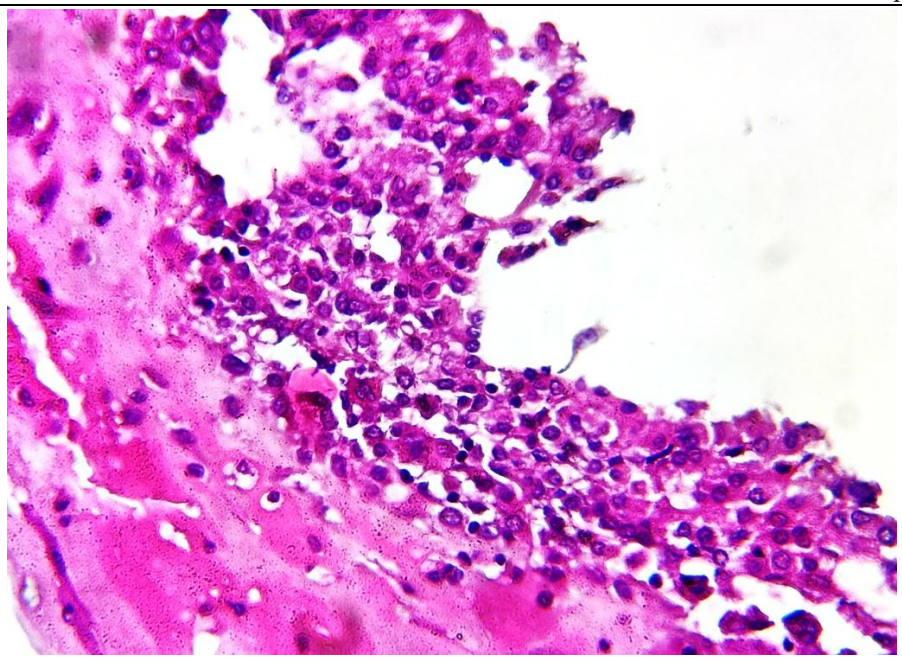

Fig. 3. Wall of a peritoneal cyst formation, with focal mesothelial proliferations, stained with *HE, magn. x 400.*

Discussion

Benign multicystic peritoneal mesothelioma is a rare tumor that occurs most often in women of reproductive age. The tumors can be multifocal or unilocular and are usually diagnosed only when they have reached a relatively large size [8]. Morphologically, the mesothelial cells lining the cysts vary from flattened to cuboidal. The cysts are thin-walled and often contain eosinophilic fluid. In some areas, their lining may also contain foci of mesothelial hyperplasia [4]. According to the WHO, the treatment of benign cystic mesothelioma should be complete surgical resection. The WHO also considers that patient follow-up is necessary, since it has been established that 50% of tumors recur after excision [7]. At the same time, these recommendations contradict another position of the WHO - to use the diagnostic category of inclusion peritoneal cyst. Benign cystic formations do not have the characteristics of tumor processes and are not classified as such because they lack the typical biological behavior of a tumor. What is the WHO's reason for this change in the name of the process remains unclear. In support of a tumor process is also the high frequency of recurrences (50%), which in turn raises the question of how benign the behavior of the tumor is.

The differential diagnosis of benign multicystic peritoneal mesothelioma includes various pathological processes in the abdominal and pelvic cavities - lymphangiomas, with cystic dilatation, containing chylous fluid (especially in young patients), local ascites around small intestinal loops, pneumatosis cystoides intestinalis, echinococcal cysts. In women, a wide range of gynecological diseases should also be considered - from ovarian cystic formations (including cystic teratomas) to cystic endosalpingiosis [1].

Pneumatosis cystoides intestinalis is a rare pathological process characterized by the presence of multiple gas-filled cysts in the submucosa or subserosa of the intestinal wall. Rupture of some cysts leads to pneumoperitoneum, which in the absence of an inflammatory process is not followed by the development of peritonitis. The condition is often an incidental finding in patients aged between 50-80 years and on imaging studies presents as asymptomatic bubbles on the intestinal wall [2, 3].

Although the incidence of cystic echinococcosis in Bulgaria is showing a downward trend (to 1.37‰, 2020), this disease is still of important medical and social importance for the country. In cases of abdominal pain and a CT scan of the abdomen, which reveals the presence of cystic formations, it is appropriate to consider echinococcosis in the differential diagnosis, the diagnosis of which can be confirmed by a positive serological result for echinococcosis by ELISA [5]. The rare organ localization of echinococcal cysts practically includes almost all organs, except the liver and lungs, where they are most often found. Cases of echinococcal cysts in the heart, CNS, skeletal muscles, mammary gland, spleen, retroperitoneum and other rare localizations have been observed, in which delayed etiological focus and clinical complications have been found. In these cases, timely qualified parasitological diagnostics, postoperative antiparasitic treatment and dispensary observation are of essential importance for adequate therapeutic behavior [5, 6]

Conclusion

Clinically diagnosed cystic masses in the abdominal cavity require a broad differential diagnosis and a multidisciplinary approach. In these cases, benign multicystic peritoneal mesothelioma should also be considered.

References

1. Alvir I. et al., Benign Multicystic Peritoneal Mesothelioma Mimicking Gynecologic Pathology, Acta Clin. Croat. 2021, Jun; 60 (2): 323-325.

2. Jandu J. et al. Case Report: Pneumatosis Cystoides Intestinalis, Rheumatologist, November 2023.

3. Pata F. and Di Sverio S., The New England Journal of Medicine, Pneumatosis Cystoides intestinalis with pneumoperitoneum, 2019, Vol. 380, No 13.

4. Pitta X. et al., Bening multisystic peritoneal mesothelioma: a case report, Med. Case Rep. 2010, Nov 29:4:385.

5. Popova G., Vutchev D., Eneva K., Masarlieva A., Familial Cystic Echinococcosis (A Case Report), IX National Conference HIV/AIDS in the pandemic Covid-19. Exotic Infectious And Parasis Diseases Collection of articles, ISBN 978-619-237-101-2 (2022) pp. 152-156.

6. Vuchev D., Masarlieva A., Bozhkov M., Rusinova Al., Eneva K., Sheitanova N., Human echinococcosis in rare organ localization, Seventh National Conference on Infectious Diseases, 2012, 59-62.

7. www.pathologyoutlines.com/caseofweek/case205.htm

8. www.pathologyoutlines.com/topic/pleuraperitmulticysticmeso.html

TRENDS AND MOTIVES IN THE POST-GRADUATE PROFESSIONAL ORIENTATION OF THE YOUNG DOCTORS OF THE 2025 CLASS OF MEDICAL UNIVERSITY-SOFIA

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ABSTRACT

The grown-up individual's need for self-affirmation is a unified whole with his professional and labor activity and with the successful realization in it. For this reason, professional choice is a complex decision-making process, determined by social and personal factors, as it is dictated not only by the needs of society, but also by the interests, opportunities, needs and inclinations of the individual. In view of this, the present article will present and analyze data from an empirical study investigating the trends, motives and conditions in the professional orientation of young doctors of the 2025 Class of Medical university-Sofia.

Keywords: trends, motives, young doctors, professional development.

INTRODUCTION

The professional division of labor arose in order to achieve the fullest use of people through their professional specialization, which in turn leads to the further development of the profession and professional differentiation. The profession represents a set of specialized and generalized functions, or knowledge, skills, work habits and formed abilities acquired through training or work, through which a person realizes himself, performing a socially useful service, determining his place in the social structure. [18, 5]

The grown-up individual's need for self-affirmation is a unified whole with his professional and labor activity and with the successful realization in it. For this reason, professional choice is a complex decision-making process, determined by social and personal factors, as it is dictated not only by the needs of society, but also by the interests, opportunities, needs and inclinations of the individual.

The choice of a profession predetermines to a large extent the life path of an individual, the development of his individual qualities and abilities, the unfolding of his essential powers, his realization as a working and social being. The labor and professional path affects the overall social behavior and social activity of the person. Educational and professional plans are the most important components of youth life plans. [18, 19, 20]

The uniqueness of the medical profession has been known since Antiquity, when the Father of Medicine, Hippocrates, in his writings "On Good Conduct" and "On the Physician" listed the rich palette of cognitive, temperamental, emotional and character qualities that a good doctor must possess. Individuals who choose the medical profession face specific professional requirements that shape their personality much more fully only when this choice meets the opportunities and interests of young people. [20, 5]

The training of future young doctors in higher medical schools in the Republic of Bulgaria is a six-year course and is regulated by the Ordinance on the Uniform State Requirements for the Acquisition of Higher Education in the Specialty "Medicine" and is conducted in accordance with the Law on Higher Education, the Law on development of the academic staff in the Republic of Bulgaria and the internal normative documents of the relevant medical university. [1, 2] The training of the medical personnel does not end with their student training, during which they acquire theoretical and practical knowledge and skills and thus build labor and theoretical training for independently solving organizational, prophylactic, treatment-diagnostic and other professional tasks. [1, 5, 6] The medical profession provides a rich opportunity for young doctors after completing their student education for postgraduate training, thus realizing the professional differentiation among doctors to ensure meeting the current and future health needs of Bulgarians citizens.

The **PURPOSE** of this article is to present and analyze the trends, motives and expectations of the young doctors of the 2025 Class of Medical university-Sofia for their post-graduate professional development.

To fulfill the goal, the following **TASKS** were set and studied:

- ✓ Research and analysis of the wishes of young doctors when choosing a specialty after completing their student studies;
- ✓ Study of the expectations of young doctors for their future realization and the prerequisites for this;
- ✓ Establishing the reasons and conditions for choosing the postgraduate professional qualification of young doctors;

MATERIALS AND RESEARCH METHODOLOGY

The object of the study is the graduating students in medicine. The technical unit of observation is Medical University - Sofia. A questionnaire survey was distributed among thethe young doctors of the 2025 Class.

The study was conducted during the October 2025 – December 2025 period in the city of Sofia and included 243 young medical doctors.

A wide range of ***sociological and statistical methods*** are used in the survey: documentary method; questionnaire survey method - medical students from MU-Sofia were surveyed with an independently developed questionnaire card; descriptive analysis; analysis of variance; Pearson's $\chi 2$ test; graphical analysis - for visualizing the results obtained. The indicators were assessed at $\alpha=0.05$ level of significance.

The quantitative analyses were performed with the SPSS 17.0 statistical software package. MICROSOFT OFFICE products were used for tabular and graphical processing and presentation.

RESULTS AND DISCUSSION

To investigate trends among young physicians from the Class of 2025 at the Medical University of Sofia regarding their choice of specialty for postgraduate training, the first question of the survey was administered. The results presented in Table 1 indicate that the most preferred specialty is Anesthesiology and Intensive Care (10.78%), followed by Pediatrics (10.29%).

Among the surgical specialties, young physicians demonstrate the greatest interest in General Surgery (8.33%), as well as in Obstetrics and Gynecology and Orthopedics and Traumatology, each accounting for 4.90%.

With respect to the therapeutic specialties, Table 1 shows that the most preferred fields among newly graduated physicians are Endocrinology (5.63%), Cardiology (4.90%), Neurology (3.75%), and Psychiatry (2.94%). It is noteworthy that young physicians from the Class of 2025 also express interest in Ophthalmology and Dermatology and Venereology. At the same time, the proportion of respondents who would choose Internal Medicine is relatively low compared to previous years (2.45%).

The trend toward pursuing primary health care remains relatively stable, with 2.945% of respondents selecting General Medicine /Family Medicine/. A total of 4.45% of participants reported that they had not yet decided which specialty within the healthcare sector they would pursue.

The planning of physicians' professional and career development is a complex process influenced by multiple determinants. Among young physicians, the leading determinants in specialty choice include, on the one hand, economic factors—namely, the opportunities provided by a given specialty for additional employment and income in private outpatient practice or in ambulatory care [10, 5]. On the other hand, determinants such as gender and personal interests in a given specialty also play a significant role, as it has been demonstrated that different medical specialties require diverse sets of skills and attributes that physicians must possess and exhibit. For example, most surgical specialties require greater-than-average physical endurance due to high workload and the unpredictability of operative duration, which has traditionally led to their characterization as "demanding" or "male-dominated."

A third group of determinants relates to working conditions, particularly the balance between personal and professional life. These factors are of critical importance, given that certain specialties are associated with heavy workloads, demanding on-call duties—including both daytime and night shifts—and work performed in both hospital and outpatient settings. Altogether, these characteristics define such specialties as burdensome to the psycho-emotional well-being of the individual, which, in turn, inevitably affects the physician's family and social environment. [10, 7, 4, 5]

Table 1.

In which field of medicine do you intend to specialize after completing your higher education?

Response	2025
Anesthesiology and Intensive Care	10.78%
Pediatrics	10.29%
Surgery	8.33%
Ophthalmology	5.88%
Endocrinology	5,63%
Dermatology	5.39%
Cardiology	4.90%
Obstetrics and Gynecology	4.90%
Orthopedics and Traumatology	4.90%
Diagnostic Imaging	3.43%
Urology	3.43%
Neurology	3.75%
General Medicine	2.94%
Psychiatry	2.94%
Gastroenterology	2.45%
Internal medicine	2.45%
Oncology	1.96%
Pathology	1.96%
Pulmonology	1.96%
Infectious Diseases	1.47%
Rheumatology	1.47%
Other/Undecided	4,45%

The second question of the survey examines young physicians' expectations regarding their future career development. The analysis of the data presented in Table 2 indicates that nearly 85% of respondents envision themselves working as physicians in clinical practice. Approximately 11% of the surveyed individuals expect to pursue careers as general practitioners or specialists in outpatient primary care.

Less than 1% of the study participants intend to develop as researchers, which would require them to continue their professional activity within a university hospital setting and to undergo a competitive selection process for obtaining an academic position at a higher medical institution, or alternatively to pursue careers as academic teaching and research staff within non-clinical departments of medical universities.

Around 2% of respondents see their professional realization as medical representatives for pharmaceutical companies, while slightly over 1% would pursue careers within governmental health institutions, engaged in the organization of the healthcare system as well as in addressing trends and challenges in public health.

Table 2.

How do you envision your future professional realization?

Response	2025
As a physician in clinical practice	84.28%
As a physician in outpatient care (GP, specialist)	11,35%
As a researcher	0,87%
As a medical representative for a pharmaceutical company	2,18%
In an administrative structure (Ministry of Health, NHIF, etc.)	1,31%

To explore respondents' expectations regarding whether they would achieve better professional realization in Bulgaria or abroad, a third question was included in the survey. The results indicate that the majority of respondents (69.00%) believe they would achieve better career development if they continue their professional path in Bulgaria, whereas 31.00% hold the opposite view (Table 3).

The analysis of these data suggests a reversal of the trend observed over the past decade, during which more than 50% of medical graduates in Bulgaria sought professional realization abroad.

Table 3.

In your opinion, where can you achieve better professional realization?

Response	2025
In Bulgaria	**69.00%**
Abroad (highly developed EU countries and the USA)	31.00%

In order to clarify the motivations among the group of young physicians who expressed a desire to pursue their careers in Bulgaria, a subsequent question was included in the empirical study. The analysis of the data presented in Table 4 shows that the leading reasons for this preference are "Family and friends" (33.45%) and "National identity and moral obligation to Bulgaria" (29.58%). These findings reflect, on the one hand, a perceived moral responsibility toward the home country, which has invested in their education and professional development, ensuring the future provision of healthcare services to Bulgarian society, and on the other hand, the importance of family and social environment.

Notably, a substantial proportion of respondents within this group (28.76%) also identify the "easier professional development in Bulgaria" as a key factor, indicating favorable opportunities for career advancement within the Bulgarian healthcare system.

To further investigate the motivations among the considerable proportion of young physicians who prefer professional realization abroad, an additional question was included in the study. The data presented in Table 5 indicate that the leading motive is "better financial remuneration" (approximately 43%), highlighting the importance of economic determinants. This is followed by "better organization of the healthcare system" in highly developed EU countries and the USA (just over 20%). Furthermore, 14.86% of respondents identify "a higher level of medical science and practice" as a motivating factor, while an equal proportion (14.86%) point to the "more difficult professional development in Bulgaria" as a reason for seeking opportunities abroad. Approximately 6.50% of respondents cite the "better standard of living abroad" as their primary motivation.

Table 4.

Your desire to pursue professional realization in Bulgaria is due to:

Response	2025
Family and friends	33.45%
National identity and moral obligation to Bulgaria	29.58%
Professional development in Bulgaria is significantly easier	28.76%
Better quality life in Bulgaria	3.45%
Higher level of medicine science and practice	2.79%
Other	1.97%

Table 5.

Your desire to pursue professional realization abroad is due to:

Response	2025
Better financial remuneration	42.45%
Better organization of the healthcare system	20.79%
Professional development in Bulgaria is significantly difficult	14.86%
Higher level of medicine science and practice	14.86%
Better quality life abroad	6.45%
Other	0.59%

The final question of the empirical study examines and analyzes the opinions of young physicians from the Class of 2025 at the Medical University of Sofia regarding the conditions necessary for their successful professional realization. As shown in Table 6, approximately half of the respondents (49.45%) identify "high-quality education" as the leading condition, encompassing material and technical facilities, teaching staff, and curricula.

Approximately 1/3 of respondents (35.75%) indicate "motivation and willingness" as the key factor, while 14.80% identify "perseverance and patience" as essential for successful professional realization.

The analysis of these data suggests that the development of medical professionals is a complex process that integrates both individual qualities and preferences, as well as numerous social determinants that are beyond the direct control of young physicians and are instead shaped by the respective state, through the organization of the healthcare system and the structure of higher medical education.

Table 6.

In your opinion, what is the most important condition for successful professional realization?

Response	2025
High-quality education (facilities, teaching staff, curricula)	49.45%
Motivation and willingness	35.75%
Perseverance and patience	14.80%

FINDINGS AND CONCLUSIONS

Based on the results of the empirical study on the conditions and trends in the career development of young physicians from the Class of 2025 at the Medical University of Sofia, it can be concluded that professional orientation is a multifactorial process that integrates both individual characteristics and preferences, as well as a wide range of societal determinants.

Evidence from the analysis indicates that a larger proportion of young physicians envision their professional careers in Bulgaria. A notable decline (approximately one-third of the total share) is observed in the previously established trend over the past decade, whereby more than half of newly graduated physicians sought professional realization abroad. Among those who still prefer to work abroad, economic determinants remain the leading motivating factors.

A substantial proportion of respondents in the study intend to pursue careers in clinical practice, selecting specialties in accordance with their personal characteristics. These choices reflect a dual objective: achieving a balance between professional responsibilities and personal life, while also securing opportunities for additional employment and income in private and outpatient medical practice.

The quality of human capital within the healthcare system is largely determined by the level of professional education and training. There exists a strong relationship between the degree of training, the potential, and the competitiveness of medical professionals, and the overall performance of the healthcare system, whose primary function is to meet the current and future health needs of the population.

Therefore, ensuring the training and development of highly qualified medical professionals is of strategic

importance for society. This is essential for the delivery of healthcare services grounded in the highest standards of medical knowledge and clinical practice, aligned with ethical principles and norms, and based on scientific evidence.

References

1. Kirkov V (2023), A training quality optimisation model for the undergraduate internship in Medical university – Sofia, Sofia 2023. PhD Thesis, Medical University of Sofia.
2. Kirkov V, Zlatanova-Velikova R, Vodenicharova Al, Leventi N (2022) Quality of the practical education during undergraduate internship at the Medical university Sofia. Acta Medica Bulgarica Journal, Vol. XLIX 4/2022, ISSN: 0324-1750, p.48-53
3. Kirkov V, Zlatanova-Velikova R (2022) Approaches and methods for quality assurance of medical education in Bulgaria regulated in normativ documents. Man, society medicine, Kardzhali, 2022, ISBN 978-954-652-037-1, pp. 380-386
4. Kirkov V (2024), The impact of the COVID-19 pandemic on the quality of higher medical education, https://pharmacia.pensoft.net/issue/4722/
5. Kirkov V, Vodenicharova A, Ivanova K, Markova K (2024) Trends and motives in the postgraduate professional orientation of the young doctors of the 2023 class of Medical University-Sofia. Pharmacia 71: 1–5. https://doi.org/10.3897/pharmacia.71.e138245
6. Kirkov V (2025) Trends in postgraduate professional orientation of young doctors graduated from the Medical University-Sofia. Pharmacia 72: 1–6. https://doi.org/10.3897/pharmacia.72.e146974
7. Kumwenda B, Cleland J, Prescott G, Walker K, Johnston P (2019). Relationship between sociodemographic factors and specialty destination of UK trainee doctors: a national cohort study. BMJ Open 2019;9:e026961. doi: 10.1136/bmjopen-2018-026961
8. Law on Higher Education in the Republic of Bulgaria (2020)
9. Papapanou M, Routsi E, Tsamakis K, Fotis L, Marinos G, Lidoriki I, Karamanou M, Papaioannou T G, Tsiptsios D, Smyrnis N, Rizos E, Schizas D (2021) Medical education challenges and innovations during COVID-19 pandemic. Postgraduate Medical Journal, Volume 98, Issue 1159, May 2022, Pages 321–327, https://doi.org/10.1136/postgradmedj-2021-140032
10. Michalik B, Kulbat M, Domagała A (2024) Factors affecting young doctors' choice of medical specialty-A qualitative study, PLoS One 2024 Feb 1;19(2):e0297927., doi: 10.1371/journal.pone.0297927
11. Ministry of health – Republic of Bulgaria. National Health Strategy 2021-2030 (2021)https://www.mh.government.bg/bg/politiki/strategii-i-kontseptsii/strategii/ proekt-na-nacionalna-zdravna-strategiya-2030/
12. Regulation No. 1 (2015) On acquiring a specialty in the health care system of the Council of Ministers, 13.06.2023
13. Regulations for the organization and activities of Medical University-Sofia, https://mu-sofia.bg/za-universiteta/normativni-dokumenti/pravilnici-mu/ found on 01.05.2024
14. Regulations for the organization and conduct of educational practices and internships at Sofia University https://mu-sofia.bg/za-universiteta/normativni-dokumenti/pravilnici-mu/ found on 01.05.2024
15. Soethout MBM, Heymans MW, Olle J (2008) Career preference and medical students' biographical characteristics and academic achievement, Medical Teacher 2008:30:1, e15–e22, doi: 10.1080/01421590701759614
16. Southworth E & Gleason SH (2021) COVID 19: A Cause for Pause in Undergraduate Medical Education and Catalyst for Innovation; HEC Forum; Published: 22 January 2021; Volume 33, pages 125–142, DOI: 10.1007/s10730-020-09433-5
17. Vodenitcharov Tz (2018) Beyond the Limits of the Possible. GorexPress
18. Vodenitcharov Tz (1986) Profession doctor. Medicine and physical education
19. Vodenitcharov Tz, Borisov V (2021) The Public Health Phenomenon in a Changing World, Second Revised Edition. Gorex Press, ISBN 978-954-616-311-0, c. 229
20. Vodenitcharov Tz (1992) Way in medicine, Sofia
21. WHO. The Global Action Plan for Healthy Lives and Well-being for All (SDG3 GAP), (2019). https://www.who.int/initiatives/sdg3-global-action-plan

ЯПОНСКИЕ ТЕХНОЛОГИИ УХОДА ЗА КОЖЕЙ: ФИЛОСОФИЯ И ПРАКТИЧЕСКОЕ ПРИМЕНЕНИЕ

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JAPANESE SKINCARE TECHNOLOGIES: PHILOSOPHY AND CLINICAL APPLICATION

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DOI: 10.5281/zenodo.20456974

АННОТАЦИЯ

В представленной статье проводится всесторонний научно-практический анализ японской системы ухода за кожей, которая гармонично объединяет многовековые традиционные философские концепции и передовые биотехнологические разработки. Главный фокус исследования направлен на философию превентивного ухода, поддержания клеточного гомеостаза и максимально бережного отношения к естественному гидролипидному барьеру эпидермиса. В работе детально разбирается практическое применение классической многоступенчатой бьюти-рутины, включающей методы атравматичного двойного очищения, глубокой гидратации и послойного нанесения косметических продуктов. Особый акцент сделан на физико-химических свойствах и инновационных методах получения активных компонентов, среди которых выделяются биосовместимые церамиды, низкомолекулярная гиалуроновая кислота, мощные антиоксиданты из зеленого чая матча и богатые аминокислотами ферментированные экстракты риса. Подробно исследуются современные высокотехнологичные трансдермальные системы доставки активных веществ, в частности липосомальные эмульсии, обеспечивающие проникновение и пролонгированное высвобождение ингредиентов в глубоких слоях дермы без структурного повреждения рогового слоя. Данный материал представляет высокую практическую ценность для дерматологов, косметологов-эстетистов и разработчиков рецептур, стремящихся адаптировать японский опыт для создания эффективных программ долгосрочного оздоровления и омоложения кожи.

ABSTRACT

The presented article provides a comprehensive scientific and practical analysis of the Japanese skin care system, which harmoniously combines centuries-old traditional philosophical concepts and advanced biotechnological developments. The main focus of the research is on the philosophy of preventive care, maintaining cellular homeostasis and taking maximum care of the natural hydrolipid barrier of the epidermis. The paper examines in detail the practical application of the classic multi-stage beauty routine, which includes methods of atraumatic double cleansing, deep hydration and layered application of cosmetic products. Special emphasis is placed on the physico-chemical properties and innovative methods of obtaining active ingredients, among which are biocompatible ceramides, low molecular weight hyaluronic acid, powerful antioxidants from matcha green tea and fermented rice extracts rich in amino acids. Modern high-tech transdermal active substance delivery systems, in particular liposomal emulsions, which ensure the penetration and prolonged release of ingredients in the deep layers of the dermis without structural damage to the stratum corneum, are being studied in detail. This material is of high practical value for dermatologists, cosmetologists, aestheticians and formulation developers who seek to adapt the Japanese experience to create effective programs for long-term recovery and skin rejuvenation.

Ключевые слова: японская косметология, J-Beauty, превентивный уход за кожей, восстановление эпидермального барьера, многоступенчатая рутина, двойное очищение, ферментация косметических ингредиентов, липосомальные системы доставки, биомиметические церамиды, глубокая гидратация дермы.

Keywords: Japanese cosmetology, J-Beauty, preventive skin care, restoration of the epidermal barrier, multi-stage routine, double cleansing, fermentation of cosmetic ingredients, liposomal delivery systems, biomimetic ceramides, deep hydration of the dermis.

Актуальность исследования. В условиях современного стремительного роста дерматологических проблем, связанных с нарушением гидролипидного барьера и повышением чувствительности кожи из-за агрессивных экологических факторов и инвазивных процедур, мировое косметическое сообщество наблюдает устойчивый сдвиг парадигмы в сторону превентивной эстетической медицины.

Японская система ухода за кожей представляет собой уникальный синтез философских традиций минимализма и передовых биотехнологий, что делает ее одним из самых востребованных направлений в современной глобальной индустрии красоты. Высокая актуальность данной темы обусловлена необходимостью глубокого научного анализа японских методик, которые предлагают физиологичный, нетравматичный подход к поддержанию клеточного гомеостаза и профилактике преждевременного старения. Это полностью отвечает растущим запросам современных потребителей и практикующих специалистов на безопасные, научно обоснованные и долгосрочно эффективные дерматологические решения, направленные на укрепление собственных защитных функций эпидермиса.

Цель исследования. Основная цель данного исследования заключается в комплексном научно-

практическом анализе концептуальной философии и инновационных технологических решений японской системы ухода за кожей для оценки их клинической эффективности в поддержании здоровья эпидермиса.

В рамках работы ставится задача детально изучить фундаментальные принципы многоступенчатого превентивного ухода, исследовать биохимические механизмы действия ключевых активных компонентов, таких как ферментированные экстракты и биомиметические церамиды, а также проанализировать физико-химические свойства современных трансдермальных систем доставки веществ, чтобы обосновать целесообразность интеграции японского опыта в международную косметологическую и дерматологическую практику.

Материалы и методы исследования. Для достижения поставленной цели был применен комплексный методологический подход, включающий систематический обзор актуальной научной литературы, монографий и публикаций в профильных дерматологических и биохимических базах данных за последние десять лет.

Материалом для исследования послужили результаты клинических испытаний эффективности традиционных японских растительных экстрактов, ферментированных комплексов и инновационных липосомальных эмульсий, а также технологические паспорта косметических рецептур ведущих азиатских лабораторий.

В работе использовались методы структурно-функционального анализа для оценки влияния японской рутины двойного очищения и послойного увлажнения на барьерные функции рогового слоя. Также применялся сравнительный анализ, позволивший сопоставить японскую концепцию бережного сохранения микробиома с агрессивными протоколами эксфолиации, и метод оценки биохимических процессов для изучения путей пролонгированного высвобождения инкапсулированных активных молекул в глубоких слоях дермы.

Результаты исследования. Развитие японской косметологии представляет собой непрерывный процесс интеграции древних культурных традиций и передовых научных достижений, берущий свое начало в эпоху Хэйан.

В древности основой ухода служили исключительно природные компоненты, такие, как вода после промывания риса, масло камелии, экстракты морских водорослей и пудра из натурального шелка, которые гейши и аристократки использовали для достижения идеала фарфоровой кожи, известного как бихаку. Важнейшим этапом стало зарождение философии бережного очищения, когда для удаления плотного макияжа применялись растительные масла, а для мягкой энзимной эксфолиации – ферментированные рисовые отруби, что исторически заложило фундаментальный принцип современного двухэтапного умывания.

Поворотным моментом в истории японских косметических технологий стала эпоха Мэйдзи во второй половине девятнадцатого века, ознаменовавшая открытие страны для западной науки и фармакологии. В этот период начали формироваться первые современные исследовательские лаборатории, выросшие из аптек западного образца, которые категорически отказались от использования традиционных, но токсичных свинцовых белил в пользу безопасных научно обоснованных рецептур.

Середина двадцатого века стала временем настоящего биохимического ренессанса, когда на фоне бурного экономического и технологического роста японские ученые сместили фокус с декоративной маскировки недостатков на превентивную терапию, поддержание клеточного гомеостаза и глубокое восстановление физиологических функций эпидермиса [4].

В семидесятые и восьмидесятые годы прошлого века японская индустрия совершила глобальный прорыв благодаря масштабным исследованиям процессов ферментации, толчком к которым послужило наблюдение за идеально гладкой кожей рук возрастных рабочих на пивоварнях по производству сакэ. Это привело к открытию уникальных дрожжевых фильтратов, богатых пептидами, витаминами и аминокислотами, а также к началу активного промышленного использования низкомолекулярной гиалуроновой кислоты и синтезу первых биомиметических церамидов для направленного восстановления гидролипидной мантии.

В двадцать первом веке японские технологии вышли на уровень молекулярной биологии и наноинженерии, представив мировому сообществу инновационные трансдермальные системы доставки активных веществ с помощью многослойных липосом и революционные формулы солнцезащитных средств с невесомыми водными текстурами, которые окончательно закрепили за японской системой ухода статус абсолютного лидера в сфере безопасной, высокотехнологичной и физиологичной антивозрастной медицины.

Отметим, что современная японская философия ухода за кожей, известная как J-Beauty, фундаментально опирается на принципы превентивной медицины, глубокого увлажнения и абсолютного уважения к защитному барьеру эпидермиса [3]. В отличие от агрессивных западных методов, нацеленных на быстрое устранение дефектов с помощью сильных кислот и жестких пилингов, японский подход пропагандирует бережное отношение к коже как к хрупкой экосистеме.

Япония является одним из мировых лидеров по инновациям в косметической химии, удерживая долю около 15-20% от всех мировых патентов в бьюти-сфере. Крупнейшие японские косметические концерны (Shiseido, Kao, Kosé) реинвестируют в исследования и разработки (R&D) от 2.5% до 3% своей годовой выручки. Это в 2 раза превышает средний глобальный показатель по индустрии красоты. Более 60% новых патентов в японском уходе за кожей направлены на борьбу с клеточным старением (Aging Care), гликацией и на защиту кожи от факторов окружающей среды.

Японский рынок ухода за кожей превысил в 2024 году 16,5 млрд долларов США с прогнозируемым ростом на 3,5% ежегодно до 2030 года, что обусловлено ежедневным использованием средств большинством населения. Статистика подчеркивает высокий спрос на натуральные и чистые продукты для фиксации кожи, а также лидерство Японии по расходам на косметику по данным Euromonitor.

Япония стабильно входит в тройку крупнейших рынков косметики в мире, уступая лишь США и Китаю. Объем японского рынка уходовой косметики (J-Beauty) оценивается примерно в 15-17 млрд долларов США ежегодно. Доля уходовых средств составляет около 45-50% от всего косметического рынка страны. Для сравнения, в странах Запада исторически лидирует декоративная косметика. Средние ежегодные траты японских потребителей на уход за кожей составляют 200-250 долларов на человека, что является одним из самых высоких показателей в мире.

Классическая японская рутина ухода состоит из 4-7 регулярных ступеней (двойное очищение, лосьон, сыворотка, эмульсия/крем, защита от солнца). Около 70-75% японских женщин используют солнцезащитные средства ежедневно круглый год, так как защита от ультрафиолета считается базой ухода и профилактики пигментации. При этом в связи с демографической ситуацией (стареющее население) антивозрастной уход (Aging Care) занимает более 30% всего объема продаж уходовой косметики.

Так же важно отметить, что Японский рынок мужской косметики демонстрирует опережающий рост (4-6% в год), обгоняя по темпам женский сегмент. Около 40% японских мужчин в возрасте от 20 до 30 лет регулярно используют как минимум два базовых средства (очищение и увлажняющий лосьон). За последние годы спрос среди мужчин на косметику для выравнивания тона кожи и сужения пор вырос на 20-25% [7].

Главным идеалом красоты является достижение эффекта моти-хада – невероятно мягкой, упругой и напитанной влагой кожи, напоминающей традиционный рисовый десерт. Эта концепция реализуется через ежедневный медитативный ритуал, где передовые научные разработки гармонично соединяются с многовековыми традициями использования ботанических экстрактов, обеспечивая долгосрочный антивозрастной результат и поддержание здорового клеточного гомеостаза [5].

Научным ядром современных японских косметических средств стали инновационные системы трансдермальной доставки активов и технологии восстановления гидролипидной мантии (рис. 1). Японские исследователи первыми в мире успешно внедрили в косметику технологию многослойных липосом – микроскопических сфер, которые безопасно транспортируют водорастворимые и жирорастворимые компоненты в глубокие слои рогового слоя, постепенно высвобождая их для пролонгированного действия.

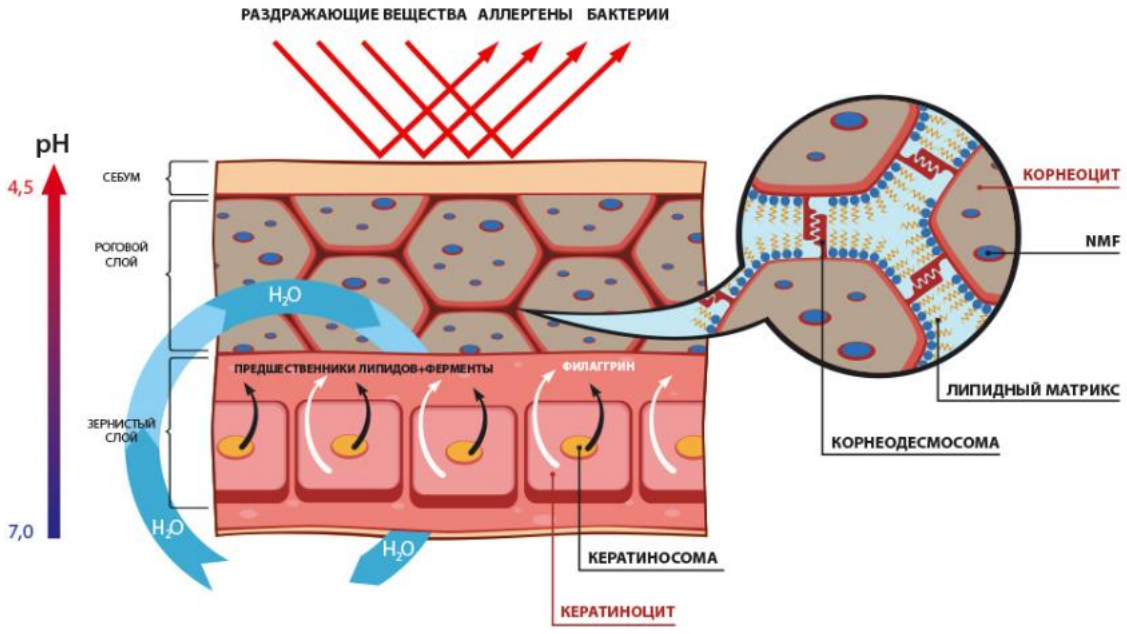

Рис. 1 – Гидролипидная мантия кожи

Кроме того, Япония выступает абсолютным лидером в области биоинженерии, разработав методы синтеза биомиметических церамидов, полностью идентичных человеческим. Эти липидные молекулы встраиваются в поврежденные участки кожного барьера, позволяя создавать невесомые эссенции, которые эффективно лечат атопический дерматит, устраняют тяжелую дегидратацию и защищают ткани от потери влаги без эффекта утяжеления или закупоривания пор (табл. 1).

Таблица 1

Методы синтеза биомиметических церамидов

№	Метод	Характеристика
1	Химический синтез	Использование защитных групп для создания специфических функциональных групп. Реакции, такие как ацилирование и алкилирование, для формирования молекул, состоящих из длинноцепочечных жирных кислот и сфингозина.
2	Ферментативный синтез	Использование ферментов, таких как сфингозин киназа, для катализа реакций, которые приводят к образованию церамидов. Этот метод может быть более экологически чистым и специфичным.
3	Биосинтетические пути	Изучение природных источников, таких как растительные или микроорганизмные культуры, которые могут вырабатывать церамиды. Изоляция и очистка церамидов из этих источников.
4	Липосомальная или наноэмульсионная технология	Включение церамидов в липосомы или наноэмульсии для улучшения их стабильности и биодоступности.
5	Комбинированные подходы	Использование комбинации химических и биохимических методов для достижения оптимальных свойств синтезируемых церамидов.

Еще одной важнейшей опорой современной японской индустрии является сложная микробиомная биоферментация и революционный подход к защите от ультрафиолета. Биотехнологические процессы с использованием дрожжевых грибков преобразуют экстракты риса, зеленого чая и сои в высокобиодоступные пептиды, аминокислоты и постбиотики, которые стимулируют обновление клеток и естественно осветляют пигментацию [1].

В сфере фотозащиты японские химики совершили глобальный переворот, разработав технологию микрокапсулирования УФ-фильтров в водные капсулы и внедрив стандартизированную систему оценки защиты от длинноволновых лучей PA++++. Благодаря этому были созданы солнцезащитные средства с текстурой воды, которые обеспечивают максимальный невидимый экран от солнца, моментально впитываются и делают ежедневное использование SPF абсолютно комфортной базовой привычкой.

Данная инновационная защита от ультрафиолета служит нерушимым фундаментом для реализации другой важнейшей японской концепции – бихаку, что означает стремление к полупрозрачной, сияющей коже с безупречно ровным тоном и полным отсутствием гиперпигментации [6]. Чтобы закрепить эффект от применения невидимых санскринов, японские лаборатории внедряют в повседневный уход передовые ингибиторы тирозиназы, такие как транексамовая кислота, альфа-арбутин и высокостабильные дериваты витамина С. Благодаря многослойным липосомальным эмульсиям эти активные вещества целенаправленно проникают к меланоцитам, блокируя избыточную выработку меланина без малейшего раздражения рогового слоя.

Параллельно с защитой и осветлением колоссальное внимание уделяется процессам клеточной регенерации с использованием технологии ферментации. Экстракты ферментированного риса, сои и дрожжевые галактомицеты естественным образом обогащают эпидермис аминокислотами, пептидами и витаминами, создавая идеальную питательную среду для поддержания здорового микробиома [2]. Новейшим вектором развития японской космецевтики стало применение растительных стволовых клеток и экзосом – микроскопических везикул, которые передают клеткам сигналы к интенсивному синтезу собственного коллагена и эластина.

На практике эти высокие технологии и философские принципы сливаются в строгую, но физиологичную систему ухода, базирующуюся на двойном очищении и интенсивном многослойном увлажнении. Ритуал неизменно начинается с использования гидрофильного масла или тающего бальзама для деликатного растворения себума и стойких солнцезащитных фильтров, после чего применяется мягкая энзимная пудра или взбитая пенка-суфле для удаления остаточных загрязнений строго без нарушения pH-баланса.

Ключевым практическим этапом выступает нанесение высокоактивного жидкого лосьона с низкомолекулярной гиалуроновой кислотой, который наносится похлопывающими движениями и работает как проводник влаги. В завершение процедуры все нанесенные сыворотки обязательно запечатываются легким молочком-эмульсией или барьерным кремом, что позволяет технологичным компонентам непрерывно работать в дерме, сохраняя абсолютное здоровье, гладкость и внутреннее сияние кожи.

Отметим, что сегодня *нарушение гидролипидной мантии* и рост чувствительности кожи из-за агрессивной экологии является ключевой проблемой современной дерматологии. Японская система решает ее через категорический отказ от травмирующих поверхностно-активных веществ в пользу физиологичного метода двойного очищения. Гидрофильные масла деликатно растворяют стойкий себум и загрязнения без механического трения, а слабокислые взбитые пенки удаляют остатки, сохраняя естественный микробиом. Для реставрации уже поврежденного барьера японские технологи

синтезировали биомиметические церамиды 1, 3 и 6 типов. Они полностью идентичны человеческим липидам и встраиваются в пустоты рогового слоя, надежно блокируя потерю влаги.

Низкая проницаемость активных компонентов сквозь плотный эпидермис долгое время снижала эффективность косметики, так как крупные молекулы оставались на поверхности. Решением проблемы стало массовое внедрение нанотехнологий и систем инкапсуляции. Японские лаборатории разработали многослойные липосомы диаметром около 0.1 микрометра. Эти микрокапсулы сливаются с клеточными мембранами и безопасно транспортируют низкомолекулярную гиалуроновую кислоту и гидролизованный коллаген глубоко в дерму, обеспечивая структурное омоложение изнутри.

Фотостарение и стойкая гиперпигментация традиционно лечились на Западе агрессивными кислотными пилингами, которые истончают роговой слой. Японская философия отвергает травматизацию, предлагая превентивный подход. Для идеальной защиты от ультрафиолета созданы невесомые эссенции на базе технологии водных капсул с микрофильтрами нового поколения. Они дают максимальный индекс защиты PA++++ без эффекта белой маски. Для осветления существующей мелазмы применяются безопасные ингибиторы фермента тирозиназы – транексамовая кислота и альфа-арбутин. Они точечно блокируют синтез меланина в меланоцитах, исключая риск воспалительных реакций.

Заключение. Японская система ухода за кожей представляет собой глубоко продуманный симбиоз многовековых восточных традиций и передовых научных достижений, где философия бережного отношения к здоровью неразрывно связана с инновационными биотехнологиями. В основе этого подхода лежит непоколебимый принцип превентивности и глубокого уважения к естественной физиологии эпидермиса, что кардинально отличается от западной тенденции к агрессивной и травматичной коррекции эстетических недостатков.

Практическое применение данной концепции выражается в строгом соблюдении ежедневных многоступенчатых ритуалов, таких как атравматичное двойное очищение и метод послойного увлажнения, которые направлены исключительно на укрепление защитного гидролипидного барьера и поддержание здорового микробиома. Интеграция высокотехнологичных систем инкапсуляции и доставки, включая нанокапсулы и многослойные липосомы, позволяет беспрепятственно транспортировать низкомолекулярную гиалуроновую кислоту, биомиметические церамиды и ферментированные экстракты глубоко в дерму, полностью исключая необходимость механического повреждения рогового слоя.

В итоге японские технологии ухода формируют не просто рутинное использование косметики, а осознанную дисциплину, где фокус намеренно смещен с кратковременного визуального эффекта на планомерное конструирование здоровой, упругой и сияющей изнутри кожи, обладающей мощным внутренним ресурсом для противостояния агрессивным факторам окружающей среды на протяжении всей жизни.

Литература

1. Andini C. et al. The study of Japanese women in the facial treatment advertisement: a semiotics perspective of Pierce's Theory //ELS Journal on Interdisciplinary Studies in Humanities. – 2022. – Т. 5. – №. 2. – С. 337-347.

2. Brucksch S., Schultz F. Ageing in Japan. Domestic healthcare technologies //German Institute for Japanese Studies Tokyo (DIJ). – 2018.

3. Grech V. S., Kefala V., Rallis E. Cosmetology in the era of artificial intelligence // Cosmetics. – 2024. – Т. 11. – №. 4. – С. 135.

4. Morganti P., Generai-Roma-ltaly I. S. Aesthetic Medicine and Cosmetology between East and West // Journal of applied cosmetology. – 2002. – Т. 20. – №. 4. – С. 247-257.

5. Sakai S. et al. Useful parameters for the motion analysis of facial skin care in Japanese women //Journal of Physiological Anthropology. – 2020. – Т. 39. – №. 1. – С. 22.

6. Tanaka K. et al. Clinical trial of low irritative skin care cosmetics in Japanese subjects with dry skin //Clinical, cosmetic and investigational dermatology. – 2020. – С. 805-814.

7. Sakti A. W. et al. Project-based learning on skin cosmetology course // Indonesian Journal of Educational Research and Technology. – 2024. – Т. 4. – №. 3. – С. 317-330.

COMPARATIVE ANALYSIS OF LONG-TERM RESULTS OF VARIOUS VOLUMES OF SURGICAL INTERVENTION FOR MULTINODULAR EUTHYROID GOITER

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DOI: 10.5281/zenodo.20456992

ABSTRACT

The airm of the study was to evaluate the long-term results of various volumes of surgical intervention for multinodular euthyroid goiter.

Material and methods: The study involved 281 patients with multinodular euthyroid goiter (MNEG) who underwent surgical treatment. Of these, 76 (27.1%) patients with bilateral MNEG underwent total thyroidectomy, 72 (25.6%) with bilateral MNEG underwent subtotal thyroidectomy, 35 (12.5%) with bilateral MNEG underwent Dunhill operation (OD), 52 (18.5%) with unilateral MNEG and 46 (16.4%) with nodular euthyroid goiter (NEG) underwent hemithyroidectomy. The age of the patients ranged from 20 to 77 years. Among them, 254 (90.4%) were women and 27 (9.6%) were men.

Results: The recurrence rate after subtotal thyroidectomy was 23.6%, after Dunhill operation was 11.4%, and after hemithyroidectomy was 11.5%. The quality of life for patients after hemithyroidectomy was significantly better: 78.8% of individuals with MNEG did not require the burden of constant hormonal therapy. Postoperative hypothyroidism was noted in 21.2% of patients who underwent hemithyroidectomy for unilateral MNEG. Patients in this group received a minimally reduced dose of levothyroxine compared to other groups of individuals (40.9±5.1 mcg) ($p<0.001$).

Conclusions Thus, performing hemithyroidectomy for unilateral MNEG represents the optimal volume of surgical intervention. However, the final choice of procedure should be a joint decision between the surgeon and the patient, made with consideration of individual risk factors for recurrence and postoperative hypothyroidism.

Keywords: multinodular euthyroid goiter, thyroidectomy, hemithyroidectomy, hypothyroidism, recurrence.

One of the essential methods for treating nodular pathology is surgery, which has been refined in recent years with the introduction of new technologies and has become safer. The concept of nodular goiter involves the presence of nodules in the thyroid gland (TG) tissue, either a single nodule (uninodular) or several nodules (multinodular), which necessitates the performance of various volumes of surgical intervention. If a single benign nodule is present, hemithyroidectomy (HT) and sufficient completion of the thyroidectomy is considered necessary. For multinodular benign goiter, the question of the volume of surgical intervention remains debatable to this day [2, 3, 5, 6]. Until the end of the last century, subtotal thyroidectomy(ST) was considered the surgery of choice for this pathology. However, the recurrence rate after its performance was high—up to 41.2%[21, 30, 31]. This ultimately prompted surgeons to transition to performing more radical volumes of surgery: total or near-total thyroidectomy(TT)[14, 20, 28]. The subsequent increase in the number of publications related to parathyroid insufficiency[31] and recurrent laryngeal nerve injury[4]. Highlights the serious side effects caused by total thyroidectomy, such as hypocalcemia, myocardial damage, and atrial fibrillation [17, 24]. Hypothyroidism, considering that hormonal therapy requires regular monitoring, represents a crucial complication for many patients. Even the fact of daily morning medication intake is burdensome for patients.

In light of the above, the performance of hemithyroidectomy in unilateral multinodular TG pathology is currently being discussed. The advantage of this volume of surgery is that it theoretically allows for the avoidance of replacement therapy with levothyroxine, and in the event of recurrence, the risk of complications after a repeat operation is reduced, since the contralateral lobe remains untouched during the primary surgery[3].

The aim of the study is evaluate the long-term results of various volumes of surgical intervention for multinodular euthyroid goiter.

Material and methods

281 patients with multinodular euthyroid goiter (MNEG) were studied, who underwent surgical treatment. Of these, 76 (27.1%) patients with bilateral MNEG underwent total thyroidectomy, 72 (25.6%) with bilateral MNEG underwent subtotal thyroidectomy, 35 (12.5%) with bilateral MNEG underwent Dunhill operation (OD), 52 (18.5%) with unilateral MNEG and 46 (16.4%) with nodulyar euthyroid gland (NEG) underwent hemithyroidectomy. The age of the patients ranged from 20 to 77 years. Among them, 254 (90.4%) were women and 27 (9.6%) were men. Was performed hormones levels TGand pituitary (T4 free and TSH), as well as ultrasound of the TG, and fine-needle aspiration biopsy (FNAB) when necessary.

Statistical analysis For the comparison of continuous variables between independent groups, parametric and non-parametric statistical approaches were applied as appropriate. When the data met assumptions of normality and homogeneity of variances, between-group differences were evaluated using Pearson's chi-squaredtest(Table 1) and t-Student test (Table 5), originally described by Student for assessing mean differences in normally distributed samples [18].

Results

Let us consider each group of operated patients with MNEG separately. 107 patients with bilateral MNEG were examined, including 72 (67.3%) who underwent subtotal thyroidectomy and 35 (32.7%) who underwent Dunhill operation. The age of the patients ranged from 20 to 70 years. Among them, there were 101 (94.4%) women and 6 (5.6%) men (Table 1). Gender analysis showed that the risk of relapse in women is 3.47 times higher than in men, p value = 0.403.

Table 1.

Characteristics of patients with MNEG who underwent ST and OD

		Young&middle-aged			Elderly		Total	OR	95%CI	P value
		19-30	31-40	41-50	51-60	61-70				
Male	N	-	1	4	-	1	6	3.47	[0.2;64.1]	0.403
	Recurrence	-	-	-	-	-	-			
Female	N	8	20	30	23	20	101			
	Recurrence	1	1	4	9	6	21			
Type of surgery	ST	5	10	23	21	13	72	2.40	[0.7;7.7]	0.145
	Recurrence	1	1	3	8	4	17			
	OD	3	11	11	2	8	35			
	Recurrence	-	-	1	1	2	4			
Duration *(years)*	up to 5	3	14	8	6	8	39	3.44	[0.9;12.4]	0.05*
	Recurrence	1	-	-	1	1	3			
	6 or >	5	7	26	17	13	68			
	Recurrence	-	1	4	8	5	18			
* Pvalue< 0.05statisticallysignificant; ST - subtotal thyroidectomy; OD - Dunhill operation										

With an increase in the volume of surgery, the frequency of MNEG recurrence decreases: after performing ST, it was 23.6% (n=17), and after OD, it was 11.4% (n=4). The Odd ration (OR) of recurrence after ST is 2.4 times higher than after OD, p value = 0.145. Furthermore, the recurrence rate increases with the age of the patients and the duration of follow-up: recurrences are more often observed in patients older than 50 years (34%) and after 6 years of postoperative follow-up (28.1%) (Table 1). Since the development of recurrence requires a certain amount of time, it must be assumed that in patients operated at a young age, unlike older patients, the possibility of recurrence development exists. Characterizing the recurrent nodules, it should be noted that less than 2 cm in size were observed in 9 (42.8%) of patients, less than 3 cm in 9 (42.8%) of patients, and only in 3 (14.3%) of patients were they larger than 3 cm. The risk of relapse increases after 6 years or more by 3.44 times than in the first 5 years, statistically significant, p value = 0.05. The group of patients who underwent TT included 76 patients with bilateral MNEG, aged 20 to 77 years. Their characteristics by sex, age, duration of follow-up after surgery, and postoperative replacement therapy are shown in Table 2.

Table 2.

Characteristics of patients with bilateral MNEG who underwent TT

Age	N	Sex		Duration of follow-up *(years)*				Hormonal status		
		Male	Female	1-2	3-5	6-10	11 and more	Euthyroid	Hypo Thyroid	Hiper Thyroid
19-30	4		4	3	-	1	-	2	1	1
31-40	13		13	3	4	4	2	7	5	1
41-50	21		21	4	4	10	2	10	10	1
51-60	19	1	18	6	6	7	-	11	7	1
61 and more	19	1	18	5	8	4	3	15	3	1
Total %	76	2 (2.6%)	74 (97.4%)	21(27.6%)	22 (28.9%)	26 (34.2%)	7 (9.2%)	45 (59.2%)	26 (34.2%)	5 (6.6%)

Table 3.

Characteristics of patients with unilateral MNEG who underwent HT

Age *(years)*	N	Sex		Duration of follow-up *(years)*			Levothyroxin intake		Hormonal status		HT	
		Male	Female	1-3	4-5	6 -10	Done	Not done	Normal	Subclin hypothyroid	Left	Right
19-30	10		10	1	7	2	2	8	8	2	4	6
31-40	10	1	9		6	4	1	9	8	2	4	6
41-50	16	4	12		11	5	2	14	14	2	7	9
51-60	10	3	7	1	6	3	3	7	9	1	4	6
61 and more	6	1	5	1	4	1	3	3	3	3	3	3
Total (%)	52	9 (17.3%)	43 (82.7%)	3 (5.8%)	34 (65.4%)	15 (28.8%)	11 (21.2%)	41 (78.8%)	42 (80.7%)	10 (19.2%)	22 (42.3%)	30 (57.7%)
HT – hemithyroidectomy												

As seen from Table 2, the predominant majority of examined patients were women (97.4%), aged 41 years and older (75%). The largest number of patients (34.2%) was observed during 6-10 years after the surgical intervention.

More than was evaluated the long –term results of surgical treatment of 52 patients with unilateral MNEG (aged 20 to 65 years). The characteristics of these patients are presented in Table 3.

As shown in Table 3, the predominant majority of patients were women (82.7%), aged 41-50 years (30.8%). Almost all patients (94.2%) were followed up for 4 to 10 years. Two or more nodules or a conglomerate of nodules were located in the right lobe in 57.7% of cases, and in the left lobe in 42.3%.

We studied the long-term outcomes of hemithyroidectomy in 46 patients with NEG (Table 4). Women accounted for 78.3% of them, men – 21.7%.

Table 4

Characteristics of patients with NEG who underwent for hemithyroidectomy

Age	N	Sex		Duration of follow-up, years			Levothyroxine intake		Hormone level		Side of HT	
		M	F	1-3	4-5	6 -13	Yes	No	Normal	Hipothyroid	L	R
19-30	9		9		8*	1*	2	7	8	1	4	5
31-40	8	1	7		6	2	2	6	7	1	5	3
41-50	14	5	9	1	12	1	1	13	13	1	6	8
51-60	10	4	6		7	3	2	8	10		5	5
61 and more	5		5		5		2	3	2	3	2	3
Total %	46	10 21,7	36 78,3	1 2,2	38 82,6	7 15,2	9 19,6	37 80,4	40 87	6 13	22 47,8	24 52,2

* - number of recurrence

Most of patients were aged 41-50 years (30.4%). A solitary nodule was located in the left lobe of the thyroid gland in 47.8% of patients, and in the right lobe in 52.2%. 82.6% of patients were follow-up for 4-5 years after surgery. 87% of all patients were in euthyroid hormonal status, only 13% had subclinical hypothyroidism (TSH up to 10 uIU/mL). Postoperative replacement therapy was received by 9 (19.6%) patients: five of them took levothyroxine -25, four - levothyroxine 50. Among these patients, 55.6% of individuals had lymphoid infiltration of thyroid tissue, hereditary genesis of the disease was noted in 44.4% of them. Only two young female patients (4.3%) had recurrencenodules measuring 5-7 mm in diameter in the contralateral lobe. Both patients had a hereditary origin of the disease, and the nodules developed in the context of adenomatous goiter. Therefore, hemithyroidectomy for NEG is the optimal volume of surgery.

A comparison of replacement therapy levels in MNEG patients who underwent various volumes of surgery is presented in Table 5.

Table 5.

Levels of replacement therapy in MNEG patients who underwent various volumes of surgical intervention (M±m)

Patientgroup	Levothyroxinedose, mcg	P(TT)	P(ST+OD)	P(HT-NEG)
TT, n=76	120,1±3,9 (50-200)			
ST+OD, n=107	99,6±4,9 (50-200)	p<0,001		
HT-MNEG, n=52	40,9±5,1 (25-75)	p<0,001	p<0,001	
HT – NEG, n=46	36,1±4,4(25-50)	p<0,001	p<0,001	p<0,05

TT- total thyroidectomy; ST - subtotal thyroidectomy; OD - Dunhill operation; HT - hemithyroidectomy

As seen from Table 5, the highest doses of levothyroxine are necessarily taken by patients who underwent TT, and approximately 2.5 times lower doses are taken by patients who underwent ST and OD, and three times lower doses are taken by patients who underwent hemithyroidectomy comparetivly.

Discussion

Lin YS et al. compared four different volumes of surgical intervention (total thyroidectomy, Dunhill operation, subtotal thyroidectomy, and hemithyroidectomy) for multinodular goiter. The recurrence rate was highest with ST (21.6%), but only 1.8% of patients required a repeat operation [25]. According to the data from this study, only 5% of patients with goiter required repeat surgery [31]. In our study, only 4 (5.5%) patients who underwent ST and had recurrence were presumed to require a repeat surgical intervention. Indications for surgery were: symptoms of compression, nodule size greater than 3 cm, conclusion of cytological examination corresponding to category *Betesda IV*. Recurrences that developed after OD were clinically insignificant. In our study, the role of a hereditary factor in the development of recurrence was confirmed: cases of repeated TG involvement were noted among 14 (66.7%) of patients with recurrence. Other authors, evaluating family history, did not find significant differences between the overall examined group and the group of individuals with MNEG recurrences [26]. Literature data on the role of replacement therapy in the development of nodular goiter recurrences are contradictory. Some authors believe that patients with MNEG require careful and individually selected replacement therapy in the postoperative period, since postoperative hypothyroidism is the driving force behind the development of nodular goiter recurrences [7, 29]. Other authors report that levothyroxine replacement or suppression therapy does not effectively prevent recurrence in patients with multinodular euthyroid goiter [27, 19]. Postoperative replacement therapy was prescribed to all patients who underwent ST and OD. As a result of the examination, the patients were divided into 3 groups. The first group – 60 (56.1%) patients - took levothyroxine in a replacement dose, regularly attended consultation with the treating physician. The second group – 31 (28.9%) patients - did not take levothyroxine, did not attend the necessary consultations, and did not regularly check the TSH level, due to the fact that their TSH levels were above the reference range during the examination. The third group consisted of 16 (14.9%) patients who took levothyroxine irregularly, with interruptions and without controlling the TSH level. Among patients with MNEG recurrences, 33.3% were individuals who took levothyroxine in the required dose, 66.7% were those who did not take or took levothyroxine in an insufficient dose; 4 (19.1%) patients took it in an insufficient dose, being in a state of hypothyroidism. The literature emphasizes the role of lymphocytic infiltration in the development of postoperative hypothyroidism and MNEG recurrence [12, 15]. After all, this activity reflects the activity of immune disorders that are a risk factor for the development of postoperative hypothyroidism, leading to recurrence [15]. In our study, lymphocytic infiltration of the TG tissue was observed in 8 (38.1%) patients with recurrences.

Analysis of the hormonal background in patients who underwent TT, revealed that 59.2% who were taking levothyroxine were in a euthyroid state; 40.8 % of patients were not compensated: some of them did not take levothyroxine at all or took it irregularly, others took it in an inadequate dose (34.2% were hypothyroid, 6.6% were hyperthyroid). In this regard, when complaints were presented, they reported a mass of complaints: weakness, bone pain, dry skin, hair loss, palpitations, irritability, etc. The above indicates that patients in the postoperative period irregularly and reluctantly visit the endocrinologist and the operating surgeon.

In patients with multinodular euthyroid goiter who present with bilateral nodules, total thyroidectomy is frequently recommended to minimize the risk of recurrence and to avoid the need for re-operation [4]. However, there are patients with asymmetric multinodular goiter, in whom several nodules or a conglomerate of nodules are located in one lobe and a share of the isthmus. Recurrence rates after hemithyroidectomy for multinodular goiter have been reported to range from 5% to 34%, and recurrence is strongly associated with the length of postoperative follow-up [22]. Recurrence can be subclinical, which occurs in most cases and is determined by ultrasound as new foci (more 5 mm) in the contralateral lobe of the thyroid gland even after primary surgery, or it can be clinically obvious in the form of a palpable nodule. Currently, hemithyroidectomy in this group of patients is a controversial and relevant issue. The reason for its performance is the low recurrence rate and postoperative hypothyroidism (23% and 31%, respectively) [23].

In our research postoperative replacement therapy was received by 11 (21.2%) patients with unilateral MNEG, 5 of whom received levothyroxinea dose of 50 μg, 5 received 25 μg, and 1 received 75 μg. Of these, 72.7% had lymphocytic infiltration of the TG tissue and

63.6% had a hereditary gene for the disease. Postoperative hypothyroidism was found in 21.2% of patients, which is consistent with the data of other authors [1, 9, 13]. Follow-up duration of 6 (11.5%) patients developed recurrence, and in all cases, a nodule with a diameter up to 1cm emerged, with a subclinical nature, revealed by ultrasound. Recurrences developed more often at a young age (up to 40 years), after 6 years of surgery in patients with a hereditary gene for the disease and those in a state of subclinical hypothyroidism. The recurrence rate after hemithyroidectomy for unilateral MNEG and after the Dunhill operation is practically identical (11.5% and 11.4%), but in the former case, a larger volume of functioning TG tissue is preserved.

Thus, in patients with nodular and unilateral multinodulareuthyroid goiter who underwent hemithyroidectomy, the following was observed low recurrence rates (4.3% and 11.5%, respectively). The incidence of postoperative hypothyroidism compensated by replacement therapy after hemithyroidectomy for NEG and MNEG is 19.6% and 21.2%, respectively, which is consistent with data from other authors [6, 7, 8, 10]. The quality of life was much better for patients after hemithyroidectomy, than for patients who underwent radical surgeries: 84.8% of patients with NEG and 78.8% of patiens with unilateral MNEG did not require burdensome hormone therapy. However, patients with hypothyroidism need a low level of postoperative replacement therapy. A comparison of levothyroxine levels taken by patients with NEG and MNEG after hemithyroidectomy revealed a non-significant ($p>0.05$) difference between the groups, consistent to 36.1±4.4 μg and 40.9±5.1 μg, respectively. Risk factors for the development of recurrence of MNEG include the patient's young age, the duration of follow-up, the absence of replacement therapy, the presence of a hereditary genesis of the disease and lymphoid infiltration. Factors predisposing to the development of postoperative hypothyroidism include lymphoid infiltration of the glandular tissue, the duration of follow-up hereditary genesis of the disease. Obtained risk factors of recurrence and postoperative hypothyroidism the same this results of many authors [6, 8, 11, 16].

Conclusions

The frequency of MNEG recurrences after subtotal thyroidectomy was 23.6%, after the *Dunhill* operation was 11.4%, and after hemithyroidectomy was 11,5%. The quality of life of patients after hemithyroidectomy was significantly better: 78.8% of individuals with MNEG did not require the burden of constant hormonal therapy. Patients in this group with hypothyroidism received a minimally reduced dose of levothyroxine compared to patients who underwent TT, ST, and OD (40.9±5.1 mcg ($p < 0.001$). Postoperative replacement therapy is insufficiently effective: 66.7% of MNEG patients with recurrences who underwent ST either did not take levothyroxine at all or took it in an insufficient dose, and 66.7% of individuals with recurrences after unilateral MNEG were in a state of subclinical hypothyroidism. Risk factors for the development of postoperative MNEG hypothyroidism include a hereditary gene for the disease, lymphocytic infiltration of the TG tissue, and duration of follow-up. Risk factors for the development of MNEG recurrence include young age of the patient, presence of replacement therapy, presence of a hereditary gene for the disease, duration of follow-up, and presence of lymphocytic infiltration. Performing hemithyroidectomy for NEG and unilateral MNEG is the optimal volume of surgery. However, the choice of this procedure for unilateral MNEG is a joint decision between the surgeon and the patient, made, taking into account risk factors for recurrence and postoperative hypothyroidism are determined individually for each patient.

References

1. Ahn D, Sohn JH, Jeon JH. Hypothyroidism following hemithyroidectomy: Incidence, risk factors, and clinical characteristics. /J ClinEndocrinolMetab. 2016;101(4):1429–1436. doi: 10.1210/jc.2015-3997.

2. Ali SZ, Baloch ZW, Cochand-Priollet B., Schmitt FC, Vielh P, VanderLaanPA.The2023 Bethesda System for Reporting Thyroid Cytopathology /Thyroid. 2023 Sep;33(9):1039-1044. doi: 10.1089/thy.2023.0141.

3. Altan N. Is lobectomy an appropriate surgical strategy for nodular goiter in endemic areas? / HaydarpasaNumune Med J 2023;63(3):241–246 DOI: 10.14744/hnhj.2021.83584

4. Altan N, Korkmaz MH, Yalçin BM, Çolak A et al. Is lobectomy an appropriate surgical strategy for nodular goiter in endemic areas? *HaydarpasaNumune Med J.* 2023;63(3):241–246. doi:10.14744/hnhj.2021.83584.

5. Altın F., Paksoy M. What should be considered in Bethesda III Thyroid nodules when preferring hemithyroidectomy or total thyroidectomy| Med Bull Haseki 2020; 58(3):293-300 doi:10.4274/ haseki. Galenos.2020.6185

6. Alwadi F., Alessa M., Alamer E, Alrabiah H. et al. Risk of malignancy in thyroid nodules Bethesda III sub classification into nuclear atypia and architectural atypia. A retrospective study/ Saudi Med J. 2025 Apr 46(4):425-428. doi: 10.15537/smj.2025.46.4.202040805.

7. Apostolou K, Misiakos EP, Pappa A, **Filippou D.**et al. Updated meta-analysis of risk factors and rates of hypothyroidism following hemithyroidectomy. *J Surg Res.*2024;293:102-120. doi: 10.1016/j.jss.2023.08.020.

8. Attaallah1 W, Erel S., Canturk N, Erbil Y. et al. and Turkish Endocrine Surgery Study Group (TESSG) InvestigatorsIshemithyroidectomy a rational management for benign nodular goitre? A Multicentre Retrospective Single Group Study/ The Netherlands Journal of MedicineJANUARY 2015, VOL. 73, NO 1, p.17-22

9. Babu RP, Christy A, Hegde A, Manjrekar P, D'Souza V. Do premenopausal Hypothyroid women on levothyroxine therapy need bone status monitoring? *Clin Med Insights Womens Health.*2015;8:2-6. doi:10.4137/CMWH.S22114.

10. Barczyński M, Stopa-BarczyńskaMHemithyroidectomy for benign euthyroid asymmetric nodular goitre. Best Pract Res/ ClinEndocrinol Metab. 2019 Aug;33(4):101288. doi:

10.1016/j.beem.2019.06.004. Epub 2019 Jun 14. PMID: 31281088 Review.

11. Bauer PS, Murray S, Clark N, et al. Unilateral thyroidectomy for the treatment of benign multinodular goiter/ J Surg Res 2013;184:514-8. 10.1016/j.jss.2013.04.045

12. Beisa V, Kazanavicius D, Skrebunas A, Simutis G et al. Prospective analysis of risk for hypothyroidism after hemithyroidectomy. /Int J Endocrinol. 2015;2015:313971. doi: 10.1155/2015/313971.

13. BolatH, Erdoğan A. Benign nodules of the thyroid gland and 25-hydroxy-vitamin D levels in euthyroid patients/ Ann Saudi Med. 2022 Apr 7;42(2):83-88. doi: 10.5144/0256-4947.2022.83

14. Boutzios G, Tsourouflis G, Garoufalia Z, Alexandraki K, Kouraklis G. Long-term sequelae of the less than total thyroidectomy procedures for benign thyroid nodular disease / Endocrine. 2019 Feb;63(2):247-251. doi: 10.1007/s12020-018-1778-y. Epub 2018 Oct 9.

15. Cao Z, Liu R, Wu M, Xu X, Liu Z. Risk factors for thyroid hormone replacement therapy after hemithyroidectomy and development of a predictive nomogram / Endocrine. 2022 Apr;76(1):85-94. doi: 10.1007/s12020-021-02971-z. Epub 2022 Jan 24.

16. Cooper D , Kaur R Ayeni F, Eslick G, EdirimanneS.Hypothyroidism after hemithyroidectomy: a systematic review and meta-analysis / Thyroid Res. 2024 Jul 8;17:18. doi: 10.1186/s13044-024-00200-z

17. Deshmukh H, Papageorgiou M, Aye M, England J et al. Hyperthyroidism and bone mineral density: dissecting the causal association with Mendelian randomization analysis./Clin. Endocrinol.(Oxf.) 2021;94:119–127. doi: 10.1111/cen.14330.

18. Ergin M, Koskan Ö. Comparison of Student – t, Welch's t and Mann – Whitney U tests in terms of Type I error rate and test power. *Selcuk J Agr Food Sci.* 2023;37(2):223-231. doi:10.15316/SJAFS.2023.022

19. Fiore E, Vitti P. Multinodular goiter. Best Pract Res ClinEndocrinolMetab. 2020;34(6):101373. doi: 10.1016/j.beem.2020.101373.

20. Gharib H, Papini E, Garber JR, Duick DS et al. American Association of Clinical Endocrinologists, American College of Endocrinology, and Associazione Medici Endocrinologi medical guidelines for clinical practice for the diagnosis and management of thyroid nodules-2016 update./ EndocrPract. 2016 May;22(5):622-39. doi: 10.4158/EP161208.GL.

21. Kamel AA, Mohamed K. Updated meta-analysis of risk factors and rates of hypothyroidism following hemithyroidectomy. *Egypt J Otolaryngol.* 2024;40:3. doi:10.1186/s43163-023-00553-6.

22. Kandil E, Noureldine SI, Yao L, Tufano RP. Current management of multinodular goiter.*Gland Surg.* 2021;10(2):629–638. doi:10.21037/gs-20-691.

23. Kaya S., Yuksek M, Sarı R, AltınO et al. Is hemithyroidectomy sufficient in unilateral benign nodular goitre? /Minerva Endocrinol (Torino). 2021 Dec;46(4):406-412. doi: 10.23736/S2724-6507.20.03203-4. Epub 2020 Sep 24.

24. Li X., Zhang T., Zhang H., Liu S., Tian L. Effects of levothyroxine therapy on bone and mineral metabolism in hypothyroidism: a systematic review and meta-analysis/ BMC Endocrine Disorders (2025) 25:11https://doi.org/10.1186/s12902-024-01819-7

25. Lin YS, Wu HY, Yu MC, Hsu CC, Chao TC Patient outcomes following surgicalmanagement of multinodular goiter: Does multinodularity increase the risk of thyroid malignancy?/ Medicine (Baltimore) 2016;95:e4194. 10.1097/MD.0000000000004194

26. Makay Ö. Less than total thyroidectomy for goiter: when and how?/Gland Surg. 2017 Dec;6(Suppl 1):S49–S58. doi: 10.21037/gs.2017.10.02

27. Rosario PW, Calsolari MR. Levothyroxine therapy does not prevent recurrence of nodules after surgery for benign multinodular goiter. *Endocrine.* 2016;51(1):124-130. doi:10.1007/s12020-015-0749-2.

28. Ross DS, Burch HB, Cooper DS, Greenlee MC et al. 2016 American Thyroid Association guidelines for diagnosis and management of hyperthyroidism and other causes of thyrotoxicosis. /Thyroid 2016;26:1343-421. doi:10.1089/thy.2016.0229

29. Ünlü MT, Yılmaz H, Korkut M, Kılıç M. Non-Toxic Multinodular Goiter: Review and Surgical Outcomes. *J Endocrinol Surg.* 2022;7(3):45-53. doi:10.5152/jes.2022.45-53

30. Yavuz HÇ. Malignancy and complication rate in reoperation of recurrent multinodular goiter after subtotal thyroidectomy. *Gaziantep Med J.* 2016;27(1):14–20. doi:10.12996/gmj.2016.05c

31. Yoldas T, Makay O, Icoz G, Kose T et al. Should subtotal thyroidectomy be abandoned in multinodular goiter patients from endemic regions requiring surgery? / Int Surg 2015;100:9-14. DOI: 10.9738/INTSURG-D-13-00275.1

PHILOSOPHICAL SCIENCES

CONSCIOUSNESS AND INTENT IN THE STRUCTURE OF HUMAN LEGAL ACTIVITY: THE PHILOSOPHICAL AND LEGAL DIMENSION

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ABSTRACT

The article provides a philosophical and legal analysis of the influence of consciousness, legal consciousness, and intent on human activity. The interrelation between the psychological, moral, and legal aspects of human behavior is examined. Particular attention is devoted to Carl Jung's concept of the collective unconscious, the problem of the formation of intent in criminal law, and the significance of legal consciousness in the process of legal certainty of human activity. The article also considers the correlation between positive and natural law, as well as the influence of moral and metaphysical categories on the formation of legal norms. It is concluded that consciousness and intent function not only as legal categories but also as philosophical categories that determine the content of human freedom, responsibility, and moral choice.

Keywords: consciousness, intent, legal consciousness, natural law, positive law, collective unconscious, freedom, responsibility, philosophy of law.

The problem of the correlation between consciousness, intent, and human activity is one of the central issues both in philosophy and in legal science. Modern law increasingly focuses not only on the external forms of human behavior but also on the internal psychological processes that determine the motivation behind human actions. In this regard, the analysis of legal consciousness, free will, moral responsibility, and intent as key categories of the philosophy of law acquires particular significance.

The legal assessment of a person's activity is impossible without examining their internal attitude toward their own actions. Therefore, the concept of intent in law is closely connected with the categories of consciousness, will, and moral choice. At the same time, contemporary philosophy of law increasingly turns to psychological concepts that allow for a deeper understanding of the nature of human behavior.

The problems of consciousness and legal consciousness have been studied in the works of both foreign and Ukrainian scholars. Sigmund Freud and Carl Jung significantly influenced the development of ideas concerning the unconscious. While Freud considered the unconscious to be the result of the repression of psychological material, Jung associated it with the existence of the collective unconscious and archetypes that shape universal models of human behavior.

In the philosophy of law, the issues of legal consciousness and the moral foundations of law were examined in the works of S. Slyvka, O. Danyliyan, M. Kostytskyi, P. Rabinovych, and other researchers. Of particular importance is the problem of the correlation between positive and natural law, as well as the search for criteria for the truthfulness of legal norms.

The purpose of the article is to conduct a comprehensive philosophical and legal analysis of the influence of consciousness and intent on human activity, as well as to investigate the interrelation between legal consciousness, morality, and legal responsibility.

Consciousness is a fundamental characteristic of human existence that determines the individual's ability to realize their own actions, evaluate their consequences, and make moral choices. In the philosophical sense, consciousness appears as a form of spiritual activity through which a person comprehends reality and their own place in the world.

For understanding the nature of legal consciousness, Carl Jung's concept of the collective unconscious is of particular importance. Unlike Sigmund Freud's psychoanalytic concept, in which the unconscious is interpreted as a result of repression, Jung believed that the human psyche contains deep structures — archetypes — that possess a universal character and are formed throughout the historical development of humankind. Archetypes function as specific behavioral models and influence moral and legal perceptions.

It was precisely at the level of the collective unconscious that primary notions of justice, prohibition, duty, and responsibility were formed. Subsequently, these notions became the basis for moral and legal norms. Thus, law is not exclusively the result of the rational activity of the state but also possesses a profound anthropological and spiritual foundation.

The philosophical analysis of consciousness allows one to assert that any legal activity of an individual is connected with an internal moral choice. A person not only complies with legal prescriptions but also correlates them with their own values, beliefs, and ideas of justice.

To understand the legal certainty of human activity, it is essential to comprehend the essence of legal consciousness. Although philosophical and legal literature contains numerous definitions of this concept, in our opinion the most successful definition interprets legal consciousness as the ideas and concepts expressing people's attitudes toward existing law and knowledge of the measure of human behavior from the perspective of rights and obligations [2, p. 174]. Here legal consciousness acts as an expression of objective social relations reflecting the dominant social and economic relations within society. On the one hand, legal consciousness finds its realization in law and justice, while on the other hand, it is itself formed under the influence of law.

Ultimately, it is impossible to identify the criterion of truth within a legal norm itself because, in this case, an entirely different external and universal criterion connected with the ontological and metaphysical spheres is necessary. When the norms of positive law originate from the norms of natural law, which in turn are rooted in the metaphysical universals of absolute good, absolute justice, and absolute truth, only then can one speak not merely of the usefulness of positive law but also of its truthfulness. Therefore, if a person attempts to deprive a legal norm of its metaphysical dimension, morality and truthfulness inevitably disappear together with it.

Legal consciousness is an important element of the spiritual life of society. It encompasses a system of legal knowledge, evaluations, beliefs, and attitudes toward law, legality, and legal order. In legal literature, legal consciousness is defined as a set of ideas and feelings reflecting people's attitudes toward existing law, rights, and obligations.

Legal consciousness is formed under the influence of social, cultural, and historical factors. On the one hand, it reflects existing social relations, while on the other hand, it itself influences the development of law and legal institutions. It is precisely through legal consciousness that individuals evaluate the fairness of legal norms and determine the boundaries of permissible behavior.

The philosophy of law considers legal consciousness not merely as a legal phenomenon but also as a form of the spiritual self-determination of a person. Law loses its humanistic content if it is deprived of a moral foundation. In this regard, the relationship between positive and natural law becomes particularly significant.

Positive law is a system of norms established by the state; however, its truthfulness cannot be determined solely through formal legality. Not every legal norm is just. Therefore, natural law acts as a specific criterion for the moral evaluation of positive law. The categories of justice, good, freedom, and human dignity possess a universal character and cannot be entirely reduced to state legislation.

Consequently, legal consciousness is not merely a reflection of legal reality but also a means of moral comprehension of law.

The concept of intent is closely connected with the concept of consciousness. In legal theory, intent is a form of guilt that signifies an individual's awareness of the socially dangerous nature of their activity. According to Article 8 of the Criminal Code of Ukraine, a crime is recognized as intentional when the person who committed it was aware of the socially dangerous nature of their action or omission, foresaw its socially dangerous consequences, and desired them — in this case, direct intent is present — or consciously allowed the occurrence of these consequences, which constitutes indirect intent. The distinction between direct and indirect intent assists in determining the gravity of guilt, the social danger of the activity, and the personality of the offender.

In general, the following elements of intent are distinguished: the intellectual element (the individual realizes the socially dangerous nature of their action or omission and foresees its socially dangerous consequences) and the volitional element (the subject desires the occurrence of socially dangerous consequences resulting from their act or consciously permits them).

At the same time, depending on the emotional aspect of the committed offense and the time of the formation of intent, the following types are distinguished: premeditated intent (when the moment of the formation of intent is separated by a period of time from its realization, during which the offender carefully prepares for the commission of the crime and considers methods of concealing it); sudden intent (the realization of intent occurs immediately after its emergence); and affective intent (arising under the influence of strong emotional excitement, suddenly, under the influence of particular circumstances, most often as a result of unlawful violence on the part of the victim), among others.

Ultimately, committing a crime under the influence of strong emotional disturbance caused by unlawful actions of the victim is considered a mitigating circumstance and, in certain cases, constitutes a mandatory feature of the so-called privileged corpus delicti.

Moreover, the issue of the influence of consciousness on the unlawful determination of the activity of mentally ill individuals requires special study. Kurt Bartol attempts to classify circumstances that may be sufficient for recognizing a person as innocent: post-traumatic stress disorder, dissociative disorder, pathological gambling syndrome, amnesia, battered woman syndrome, and compulsive sexual behavior syndrome [1, p. 138].

A person who constantly exists within society faces a choice between the legal and illegal determination of their activity. They have the right to understand what exactly is required of them and what boundaries are imposed upon them.

Special attention should be paid to the problem of the influence of mental states on legal responsibility. Contemporary legal psychology investigates various mental disorders that may affect a person's ability to understand the significance of their actions or control them.

Kurt Bartol emphasizes such mental conditions as post-traumatic stress disorder, dissociative disorders, pathological addiction, and other syndromes that may

influence human behavior. In certain cases, such conditions may constitute grounds for mitigation of responsibility or for declaring a person legally insane.

The state of strong emotional excitement (affect) is of particular importance. Ukrainian legislation recognizes that a crime committed under the influence of strong emotional disturbance may be considered a mitigating circumstance.

The philosophical aspect of this issue lies in determining the boundaries of human free will. If a person's consciousness is substantially impaired, the question arises concerning the possibility of a полноцен moral choice. Therefore, law must consider not only the external result of an action but also the internal psychological state of the individual.

The philosophy of law is impossible without addressing the problem of truth and justice. Positive law itself cannot serve as an absolute criterion of truth because a law may be formally valid yet unjust.

In this context, the concept of natural law acquires special significance. According to this concept, the source of law is universal moral principles. The ideas of absolute good, justice, and human dignity possess a metaphysical character and constitute the foundation of the legal system.

Depriving law of its moral and spiritual dimension leads to the loss of its humanistic essence. Law ceases to function as a means of protecting the individual and becomes merely a mechanism of coercion. Therefore, the philosophical comprehension of law is a necessary condition for the formation of a rule-of-law state and civil society.

Thus, consciousness and intent are not merely psychological or legal categories but also important elements of the philosophical understanding of the human being. Consciousness determines the individual's capacity for moral choice, while intent functions as a form of realization of free will within the legal sphere. Legal consciousness ensures the internal connection between law and morality, whereas natural law serves as a criterion for evaluating the justice of positive law. Philosophical and legal analysis allows one to conclude that legal responsibility must take into account not only the external nature of an action but also the internal spiritual and psychological condition of the individual. Consequently, law cannot exist in isolation from the moral, spiritual, and anthropological foundations of human existence.

The conducted analysis demonstrated that human legal behavior is formed under the influence of a complex interaction of rational, volitional, emotional, and spiritual factors that determine an individual's ability to realize their own actions and foresee their consequences.

The study of Carl Jung's concept of the collective unconscious made it possible to establish that legal consciousness possesses not only a social but also a profound anthropological dimension. Archetypal notions of justice, responsibility, prohibition, and order became the basis for the formation of moral and legal norms, which testifies to the spiritual foundation of law.

In turn, intent functions as an important form of expressing human free will within the legal sphere. Through the intellectual and volitional components of intent, the internal attitude of a person toward their own behavior and its consequences is revealed. This makes it possible to assert that legal responsibility is impossible without taking into account the conscious nature of human activity.

Particular significance is attached to the problem of the influence of a person's mental state on their ability to understand the significance of their actions and control them. In this regard, modern law must consider not only the external aspect of an offense but also the internal spiritual and psychological state of the individual.

At the same time, the article proves that a legal norm cannot be completely separated from its moral and metaphysical dimension. Positive law acquires the characteristics of justice only when it is based on the principles of natural law, human dignity, freedom, and good. Depriving law of moral content leads to the loss of its humanistic essence and truthfulness.

Thus, the philosophical and legal analysis of consciousness and intent allows for a deeper understanding of the nature of human legal activity, the mechanisms of the formation of legal responsibility, and the significance of spiritual and moral factors in the legal life of society.

References

1. Bartol K., Bartol A. *Psychology of Criminal Behavior*. Translated from English. Kyiv: Tsentr Uchbovoi Literatury, 2016. 640 p.

2. Danyliyan O. H., Dzoban O. P. *Philosophy of Law*. Kharkiv: Pravo, 2017. 432 p.

3. Kostytskyi M. V. *Philosophy of Law: Problems of Methodology*. Kyiv: Yurinkom Inter, 2008. 336 p.

4. Rabinovych P. M. *Fundamentals of the General Theory of Law and the State*. Lviv: Krai, 2007. 192 p.

5. Slyvka S. S. *Philosophy of Law*. Kyiv: Atika, 2012. 256 p.

6. *Philosophy of Law*. Edited by O. H. Danyliyan. Kharkiv: Pravo, 2009. 208 p.

7. *Philosophical Encyclopedic Dictionary*. Edited by V. I. Shynkaruk. Kyiv: Abrys, 2002. 742 p.

8. Jung C. *Archetypes and the Collective Unconscious*. Lviv: Astroliabiia, 2013. 608 p.

9. *Criminal Code of Ukraine: Current Legislation as of 2026*. Kyiv: Alerta, 2026.

ГРОМАДЯНСЬКЕ СУСПІЛЬСТВО ЯК ПРОСТІР ПОДОЛАННЯ ЕКЗИСТЕНЦІЙНОЇ КРИЗИ: ДОСВІД СУЧАСНОГО УКРАЇНСЬКОГО СОЦІУМУ

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CIVIL SOCIETY AS A SPACE FOR OVERCOMING THE EXISTENTIAL CRISIS: THE EXPERIENCE OF MODERN UKRAINIAN SOCIETY

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DOI: 10.5281/zenodo.20457024

АНОТАЦІЯ

У статті здійснено комплексний теоретико-методологічний аналіз трансформації українського громадянського суспільства в умовах тривалого екзистенційного виклику. Метою цієї статті є концептуально-аналітичне дослідження українського громадянського суспільства як унікального суспільного та комунікативного простору, що не лише нівелює матеріальні та логістичні наслідки війни, але й виступає терапевтичним інструментом подолання колективної екзистенційної кризи, забезпечуючи відновлення індивідуальної та групової суб'єктності через практики солідарності. Досліджено механізми, за допомогою яких третій сектор нівелює прояви колективної травми, деструкції життєвого світу та кризи індивідуальних сенсів. Особливу увагу приділено динаміці краудфандингу та соціально-психологічним аспектам відновлення суб'єктності через практики волонтерства.

ABSTRACT

The article provides a comprehensive theoretical and methodological analysis of the transformation of Ukrainian civil society in the face of a prolonged existential challenge. The aim of this article is a conceptual and analytical study of Ukrainian civil society as a unique social and communicative space that not only offsets the material and logistical consequences of war, but also acts as a therapeutic tool for overcoming the collective existential crisis, ensuring the restoration of individual and group subjectivity through solidarity practices. The mechanisms by which the third sector mitigates manifestations of collective trauma, destruction of the life world, and crisis of individual meanings are explored. Particular attention is paid to the dynamics of crowdfunding and the socio-psychological aspects of restoring subjectivity through volunteering practices.

Ключові слова: громадянське суспільство, екзистенційна криза, волонтерський рух, краудфандинг, суб'єктність, онтологічна безпека, солідарність, інституціоналізація.

Keywords: civil society, existential crisis, volunteer movement, crowdfunding, subjectivity, ontological security, solidarity, institutionalization.

Повномасштабна військова агресія Російської Федерації проти України актуалізувала перед українською нацією виклики, які за своїми масштабами виходять далеко за межі класичних політичних, економічних чи безпекових криз [4, 12].

Вони набули вираженого екзистенційного характеру, оскільки поставили під загрозу саме право на існування українського етносу, його суверенної державності та системи соціокультурних цінностей. У ситуації, коли традиційні інституційні механізми держави зазнали колосального тиску, головним стабілізуючим фактором та інфраструктурою національної стійкості виступило громадянське суспільство [1; 3].

Екзистенційна криза на рівні цілого суспільства виникає тоді, коли під загрозою повного знищення опиняються його базові константи: колективна ідентичність, історична пам'ять та безпековий простір. Для сучасного українського суспільства ця криза матеріалізувалася у формі кількох взаємопов'язаних деструктивних факторів. Зокрема, це руйнування життєвого світу (Lebenswelt): війна знищила передбачуваність повсякденного буття, позбавивши мільйони громадян базового почуття онтологічної безпеки. Також вона стала для багатьох колективною травмою і тим самим запустила

механізм депресії: масові втрати, вимушена міграція та постійна загроза фізичного знищення сформували хронічний стрес та дезорієнтацію [7, с. 89].

Врешті відбувається криза індивідуальних сенсів, тобто так звана руйнація довгострокового планування, що породжує феномен «тимчасовості існування», коли суб'єкт втрачає мотивацію до цілепокладання.

За умов, коли державний апарат змушений фокусуватися переважно на макрорівневому оборонному та фінансовому менеджменті, мікро- та мезорівні подолання цієї деструкції заповнюють недержавні актори - організації громадянського суспільства (ОГС), волонтерські мережі та неформальні об'єднання [2]. Громадянське суспільство стає своєрідним терапевтичним каркасом, що перекладатиме деструктивний страх небуття в конструктивне русло соціальної дії.

Трансформаційна стійкість українського громадянського суспільства - це унікальна здатність громадського сектору, волонтерських ініціатив та пересічних громадян не лише виживати в умовах екзистенційних загроз (повномасштабна війна), а й швидко адаптуватися, змінюватися та ставати сильнішими, забезпечуючи при цьому функціонування держави та захист демократичних цінностей [1, 3].

Основні складові та характеристики цієї стійкості у 2025–2026 роках:

1. Висока суб’єктність та адаптивність: громадянське суспільство трансформувалося з інструменту контролю влади на ключового партнера, що забезпечує «низовий» суверенітет. Це підтверджує здатність до самоорганізації, яка не потребує вказівок зверху.

2. Стійкість як партнерство: сталий громадський сектор сьогодні базується на партнерстві, стратегічному плануванні та фінансовій незалежності, переходячи від моделі «виживання» до моделі «розвитку».

3. Соціальна консолідація: попри серйозні виклики війни, суспільство консолідується навколо спільних цінностей, що робить його стійким до внутрішніх та зовнішніх потрясінь.

4. Функція противаги: навіть в умовах воєнного стану громадянське суспільство зберігає свою демократичну функцію - контроль за владою та запобігання авторитаризму, що є основою європейської інтеграції України.

Варто зазначити, що основними факторами формування стійкості є:

- **самоорганізація** (здатність створювати нові форми недержавних організацій (наприклад, волонтерські штаби);
- **правосвідомість** (високий рівень правової культури громадян, які знають свої права та обов'язки);
- **взаємодія з державою** (громадянське суспільство виступає соціальною основою держави, активно впливаючи на прийняття рішень (лобізм).

Трансформаційна стійкість дозволяє українському суспільству не лише протистояти агресії, а й трансформувати країну в напрямку більш демократичного та вільного устрою.

Волонтерський рух в Україні став основним механізмом швидкого реагування, забезпечуючи армію та потерпілих, що врешті підвищує соціальну довіру. Створення неформальних мереж допомоги виявилися на сьогодні набагато гнучкішими за бюрократичні структури. Кількість громадських організацій та благодійних фондів свідчить про високий рівень довіри та соціальної активності в країні.

Емпіричним підтвердженням стійкості та залученості громадянського суспільства є обсяги національного краудфандингу. За даними моніторингових звітів, фінансові збори найбільших фондів (таких як «Повернись живим», «Фонд Сергія Притули» тощо), а також мікродонати на приватні банківські «банки» продемонстрували феномен солідарного оподаткування [5; 6].

Громадянське суспільство нівелює екзистенційну кризу не лише через постачання матеріальних ресурсів, а насамперед через специфічні соціально-психологічні механізми, зокрема повернення собі суб’єктності і агентності а також реінтеграцію соціального капіталу через ОГС (організації громадянського суспільства). Війна розриває звичні родинні та територіальні зв'язки. Громадські простори, хаби для внутрішньо переміщених осіб (ВПО) та благодійні фонди створюють нові горизонтальні зв'язки. Солідарність та терапевтичний ефект спільної праці мінімізують прояви «вини вцілілого» та інтегрують маргіналізовані верстви соціуму.

Головним симптомом екзистенційного відчаю є відчуття безпорадності перед обличчям глобальної загрози. Включення особистості у волонтерську діяльність чи локальні громадські ініціативи миттєво повертає їй відчуття контролю за ситуацією. Індивід перетворюється з пасивного «об'єкта військових дій» (жертви) на «суб'єкта опору» (актора). Формула «активність» - «зменшення тривоги» стала базовим психотерапевтичним алгоритмом українського соціуму.

Саме всередині громадянського сектору артикулюються відповіді на питання «за що ми боремося?» та «якою буде Україна майбутнього?». Це простір, де кристалізуються цінності свободи, верховенства права та європейського вибору, які заміщують страх смерті раціональним прагненням розвитку держави [2].

Зрештою в Україні відбувається генерація макронаративів і життєствердного сенсотворення. Громадянське суспільство формує етику відповідальності, яка стає основою нової політичної культури України.

Незважаючи на високу життєздатність, на сучасному етапі (2025–2026 рр.) український громадський сектор стикається із системними внутрішніми та зовнішніми загрозами, які загрожують його довгостроковій стабільності. А саме:

1) Емоційне вигорання та втома людського капіталу: ресурс солідарності не є безмежним. Тривала волонтерська діяльність у режимі надзусиль без належної психологічної та матеріальної підтримки призводить до глибокого професійного виснаження активістів [5]. Починає відчуватися дефіцит

кадрів через мобілізаційні процеси та міграційні хвилі.

2) Економічне виснаження та фінансова турбулентність: побудова фінансових моделей переважно на мікрозборах ускладнюється через падіння реальних доходів населення. ОГС змушені диверсифікувати джерела надходжень, поєднуючи міжнародні гранти, соціальне підприємництво та державне замовлення на соціальні послуги [6].

Періодично фіксуються спроби обмеження діяльності антикорупційних, екологічних та правозахисних організацій з боку окремих владних груп під приводом воєнного стану. Окрім того, третій сектор стає мішенню цілеспрямованих ворожих дезінформаційних операцій, спрямованих на підрив суспільної довіри до волонтерів та благодійних інституцій

Громадянське суспільство у сучасній Україні виконує принципово нову історичну роль. Воно трансформувалося з механічної сукупності інституцій у живий, адаптивний **соціально-комунікативний простір**, який став головною противагою тотальній екзистенційній кризі нації.

Через інструменти горизонтальної взаємодії, волонтерського руху та локальної самоорганізації український соціум успішно долає загрозу дезінтеграції та психологічного надлому.

Подальша стійкість цього простору залежатиме від здатності ОГС до інституціоналізації, професіоналізації та збереження балансу у взаємодіях із державними органами влади при неухильному дотриманні демократичних стандартів. Участь у практиках громадянського сектору повертає індивіду втрачену через війну суб'єктність, реконструює зруйнований життєвий світ та наповнює буття новими сенсами. Громадянське суспільство активно бере участь у створенні нового українського наративу, об'єднуючи людей навколо цінностей гідності і свободи.

Український соціум функціонує як простір, де індивідуальна трагедія перетворюється на колективний опір, а екзистенційний страх - на дієву солідарність, забезпечуючи життєздатність української нації.

Література

1. Алфавіт громадянського суспільства. Державна прикордонна служба України. 2023. URL: https://dpsu.gov.ua/uk/abetka-gromadyanskogo-suspilstva

2. Громадянське суспільство в Україні: особливості формування та розвитку. Журнал правових досліджень. 2024. URL: https://jpl.donnu.edu.ua/article/view/14873 .

3. Громадянське суспільство України в умовах війни 2022–2025: динаміка татренд досліджень. ICAPЄднання. 2025. URL: https://home.ednannia.ua/analytics/data-catalog/491

4. Екзистенційні виклики для України у війні з РФ. ResearchGate. 2024. URL: https://www.researchgate.net/publication/378354895_Ekzistencijni_vikliki_dla_Ukraini_u_vijni_z_RF

5. Тягнирядно Л. Громадянське суспільство України на четвертий рік повномасштабної війни: від кризи до стійкості. Центр прав людини ZMINA. 2025. URL: https://zmina.info/articles/gromadyanske-suspilstvo-ukrayiny-na-chetvertyj-rik-povnomasshtabnoyi-vijny-vid-kryzy-do-stijkosti/

6. Тягнирядно Л. Війна, внутрішній тиск і фінансова турбулентність: як громадянське суспільство України пережило 2025 рік. ZMINA. 2026. URL: https://zmina.info/articles/vijna-vnutrishnij-tysk-i-finansova-turbulentnist-yak-gromadyanske-suspilstvo-ukrayiny-perezhylo-2025-rik/.

7. Українське суспільство в умовах війни. Рік 2023: Колективна монографія / за ред. Є. Головахи, С. Макєєва. Київ: Інститут соціології НАН України, 2023. 343с. URL: https://isnasu.org.ua/assets/files/monitoring/Maket_Ukr_suspilstvo_2023.pdf

PHYSICS AND MATHEMATICS

RβG^-CLOSED SETS IN TOPOLOGICAL SPACES

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DOI: 10.5281/zenodo.20457036

ABSTRACT

Firstly, we introduce the concept of rβg^-closed sets as a new type of g-closed sets. Then, we investigate some properties of them. We obtain that it is is stronger than both rg-closed and rβg-closed. Then, we give a diagram. Besides, we define a complement of it and give a charactierization and some properties similarly.

Keywords: g-closed sets, rg-closed sets, wsr-sets, rβg-closed sets, rβg^-closed sets.

1. INTRODUCTION

Of course, open sets and so closed sets are the basic notions of point-set topology. Levine[5] introduced the notion of generalized closed sets as a generalization of closed sets. Then, Dunham[2] defined the notion of the closure operator cl* and investigated properties of them. Besides, he introduced a topology τ^* and related interior operator int*. Several authors studied on g-closed sets such as [3],[4],[6],[7]. In fact, the purpose of this study is to introduce a new type of g-closed sets namely rβg^-closed sets. Topology is a special subcollection of P(Z) such that P(Z) is power set of Z. We use the symbol (Z,τ) for a topological space. For a subset X of Z, the closure of T and the interior of T are denoted by cl(T) and int(T), respectively in a space (Z,τ). It is known that a subset T is said to be regular open (resp. regular closed) [9] if T=int(cl(T)) (resp. T=cl(int(T))).

2. PRELIMINARIES

In this section we recall necessary definitions.

Definition 2.1. A subset X of a topological space (Z,τ) is called

(1) β-open[1] if cl(int(cl(X))),

(2) β-closed[1] if (Z-X) is β-open,

(3) β-regular[6] or weak semi-regular set[3](briefly, wsr-set) if X is both β-open and β-closed.

Definition 2.2. A subset X of a topological space (Z,τ) is called

(1) generalized closed (briefly, g-closed)[5] if $cl(X)\subseteq U$ whenever $X\subseteq U$ and U is open in Z,

(2) regular generalized closed (brifly, rg-closed)[7] if $cl(X)\subseteq U$ whenever $X\subseteq U$ and U is regular open in Z,

(3) rβg-closed [4] if $cl(X)\subseteq U$ whenever $X\subseteq U$ and U is wsr in Z,

(4) generalized open (briefly, g-open)[5] if (Z-X) is g-closed.

WSR(Z), GC(Z) and GO(Z) denotes the collection of all wsr-sets, g-closed sets and g-open sets in (Z,τ), respectively.

Lemma 2.3. If $X\in$ WSR(Z), then $(Z-X)\in$ WSR(Z)[3].

Lemma 2.4. In any topological space (Z,τ), the following properties are hold:

(1) Every closed set is g-closed[6].

(2) Every g-closed set is rg-closed[7].

(3) Every closed set is rβg^-closed[4].

Corollary 2.5. Every closed set is rg-closed.

Definition 2.6. For a subset X of a topological space (Z,τ), the generalized closure operator cl*[2] is defined bythe intersection of all g-closed sets containing X, i.e., $cl^*(X)=\cap\{F\subseteq Z: X\subseteq F\in GC(Z)\}$.

Lemma 2.6. cl* is a Kuratowski Closure Operator. [2]

The next definition is given in [2].

Definition 2.7. Let a subset X of a topological space (Z,τ).

(1) $\tau^*=\{X:cl^*(Z-X)=Z-X\}$ is a topology on Z.

(2) $int^*(X)=\cup\{V\subseteq Z:V\in GO(Z), V\subseteq X\}$

(3) If $X\in\tau^*$, then X is called τ^*-open,i.e., $int^*(X)=X$.

(4) If $(Z-X)\in\tau^*$, then X is called τ^*-closed,i.e., $cl^*(X)=X$.

Lemma 2.8. For the subset X of a topological space (Z,τ), then the next relations are hold:

(1) $cl^*(X)\subseteq cl(X)$,

(2) $\tau\subseteq\tau^*$.

3. RβG^-CLOSED SETS AND RβG^-OPEN SETS

In this section, we define a type of generalized closed sets using wsr-set and cl* operator and investigate some properties of it. Besides we introduce complement of it as a new type of g-open sets.

Definiton 3.1. A subset X of a topological space (Z,τ) is called

(1) rβg^-closed if $cl^*(X)\subseteq U$ whenever $X\subseteq U$ and U is wsr-set in Z,

(2) rβg^-open set if (Z-X) is a rβg^-closed.

Theorem 3.2. In any space (Z,τ), every closed set is rβg^-closed.

Proof. Let $X\subseteq Z$ is closed set and $X\subseteq U\in WSR(Z)$. Then, $cl(X)=X\subseteq U$. From Lemma 2.1, we have $cl^*(X)\subseteq cl(X)\subseteq U$ and hence $cl^*(X)\subseteq U$. Therefore, $cl^*(X)\subseteq U$ whenever $X\subseteq U$ and U is wsr in Z. This shows that X is rβg^-closed.

Corollary 3.3. rβg^-closedness is a generalization of closedness.

Remark 3.4. The converse of the above theorem need not be true as seen from the next example.

Example 3.5. Consider the topological space Z={a,b,c,d} with topology τ={∅,Z,{a},{b,d},{a,b,d}}. Then, X={b,c} is a rβg^-closed but not closed.

Theorem 3.6. In any space (Z,τ), every rβg-closed set is rβg^-closed.

Proof. The proof is obvious from Lemma 2.8(1).

Remark 3.7. The converse of the above theorem need not be true as seen from the next example.

Example 3.8. Let (Z,τ) be a topological space and X={b,c} be a subset of Z as in Example 3.5. Then, X={b,c} is a rβg^-closed but not rβg-closed.

Proposition 3.9. In any space (Z,τ), every regular open set is wsr-set.

Proof. Let X is a regular open set in Z. Then, X=int(cl(X)) and we have cl(X)=cl(int(cl(X))) by taking closure. Hence X⊆cl(int(cl(X))) and this shows that X is β-open set. On the other hand, since X is regular open set it is open. Then, we have X=int(X). By taking closure and interior respectively, cl(X)=cl(int(X)) and X=int(cl(X))=int(cl(int(((X))). Hence int(cl(int(((X)))⊆X and this shows that X is β-closed. Eventually, X is wsr-set from Definition 2.1(3).

Theorem 3.10. In any space (Z,τ), every rg-closed set is rβg^-closed.

Proof. This proof is obtained by using Definition 2.2(2), Lemma 2.8, Definition 3.1 and Proposition 3.9.

Remark 3.11. The converse of the above theorem need not be true as seen from the next example.

Example 3.12. Let (Z,τ) be a topological space and X={b,c} be a subset of Z as in Example 3.5. Then, X={b,c} is a rβg^-closed but not rg-closed.

Remark 3.13. We have the next diagram using Corollary 2.5, Theorem 3.2, Theorem 3.6 and Theorem 3.10.

closed set → rg-closed set
↓ ↓
rβg-closed set → rβg^-closed set
Diagram

One can the following fact using above diagram with Lemma 2.4(1) and Lemma 2.4(2).

Corollary 3.14. rβg^-closedness is a new generalization of g-closedness.

Now, we give a property of rβg^-closed sets.

Theorem 3.15. Let (Z,τ) be a topological space and X⊆Z. If X is rβg^-closed, then (cl*(X)-X) contains no non-empty wsr-set.

Proof. Let U∈WSR(Z) such that U⊆(cl*(X)-X). Then, U⊆(Z-X) and so X⊆(Z-U). Using X is rβg^-closed and (X-U) is wsr-set, cl*(X)⊆(X-U) and U⊆ (Z-cl*(X)). So, U⊆ [cl*(X)∩(Z-cl*(X))] =∅. Therefore, U is empty.

Theorem 3.16. Let (Z,τ) be a topological space. If X⊆Z is a rβg^-closed set and X⊆Y⊆cl*(X), then Y⊆Z is a rβg^-closed.

Proof. Let X be a rβg^-closed set such that X⊆Y⊆cl*(X). Let U be a wsr- set of Z such that Y⊆U. Since X is a rβg^-closed, we have cl*(X)⊆U. According to Lemma 2.6 since cl* is a Kuratowski Closure Operator, we obtain that cl*(X)⊆cl*(Y)⊆cl*(cl*(X))=cl*(X)⊆U and hence cl*(Y)⊆U. So, U⊆Z is a wsr-set and Y⊆Z is a rβg^-closed.

Corollary 3.17. Let (Z,τ) be a topological space. If X⊆Z is a rβg^-open set and int*(X)⊆Y⊆X, then Y⊆Z is a rβg^-open.

Proof. This proof is obtained from Theorem 3.16 and Definition 3.1.

Theorem 3.18. Let X be a subset of a topological space (Z,τ). X is rβg^-open set if and only if U⊆int*(X) whenever U⊆X for any wsr-set U in Z.

Proof. Necessity: Let X is rβg^-open set and U∈WSR(Z), where U⊆X. Then, (Z-X) is a rβg^-closed and (Z-X)⊆(Z-U). From Lemma 2.4, (Z-U) is a wsr-set in Z and hence cl*(Z-X)=(Z-int*(X))⊆(Z-U). So, it is clear that U⊆int*(X).

Sufficiency: Let U⊆int*(X) whenever U⊆X and U∈WSR(Z). Then, (Z int*(X))=cl*(Z-X)⊆(Z-U) whenever (Z-X)⊆(Z-U)∈WSR(Z) from Lemma 2.4.. Hence, (Z-X) is rβg^-closed set and consequently X is rβg^-open.

Theorem 3.19. If X and Y are rβg^-open sets, then (X∩Y) is rβg^-open.

Proof. Let U⊆(X ∩Y) and U be a wsr set in Z. Since X and Y are rβg^-open sets, we obtain that U⊆int*(X) and U⊆ int*(Y). Besides, according to Definition 2.7(2) and Theorem 3.18, (X∩Y) is rβg^-open.

Corollary 3.20. If F and K are rβg^-closed sets, then (F∪K) is rβg^-closed.

Proof. The proof is obtained by Definition 3.1 and Theorem 3.19.

We have the next fact as conclussion of Corollary 3.20.

Remark 3.21. RβGC(Z) is closed under finite union.

Acknowledgement: This paper is a part of MsC Thesis of first author.

4. RESULTS AND DISCUSSION

The notion of generalized closed sets is an important subject on topological spaces. So, we have devoted this article to investigating a new generalization of closed sets which name is rβg^-closed. We give some properties of these sets. We introduce the notion of rβg^-open set as complement of rβg^-closed set and obtain some properties of them. Our future plan will focus on separation axioms of rβg^-open sets and study on continuity using what we can get.

References

1. Abd-El Monsef, M. E., El-Deeb, S. N. and Mahmoud, R. A., β-open sets and β-continuous mapping, Bull. Fac. Sci. Assiut Univ. 12 (1983), 77-90.

2. Dunham, W., A new closure operator for non-T_1 topologies, Kyungpook Math. J., 22 (1982), 55-60.

3. Keskin, A. and Hatir, E., A decomposition of continuity, Centenary Year University, J. Inst. Nat. Appl. Sci., XVI. National Math. Symposium, Special Vol., Jan. 2005, pp. 209-216.

4. Keskin Kaymakci, A., Noiri, T. and Parimala, M., Regular β-generalized closed sets, Far East Journal of Mathematical Sciences(FJMS),140(1)(2023), 47-58.

5. Levine, N., Generalized closed sets in topology, Rend. Circ. Mat. Palermo 2 (1970), 89–96.

6. Noiri, T., Weak and strong forms of β-irresolute functions, Acta Math. Hungar., 99(4)(20023), 315-328.

7. Palaniappan, N. and Rao, K. C., Regular generalized closed sets, Kyungpook Math. J., 33 (1993), 211-219.

8. Stone, M. H., Application of the theory of Boolean rings to general topology, Trans. Amer. Math. Soc., 41 (1937), 375-381.

TECHNICAL SCIENCES

СОВМЕЩЕНИЕ ЭТАПОВ ПАРАМЕТРИЧЕСКОЙ ИДЕНТИФИКАЦИИ И ОПТИМИЗАЦИИ ДИНАМИЧЕСКИХ ПРОЦЕССОВ

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COMBINING THE STAGES OF PARAMETRIC IDENTIFICATION AND OPTIMIZATION OF DYNAMIC PROCESSES

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АННОТАЦИЯ

В данной работе представлен единый подход к одновременному решению двух традиционно разделяемых задач в теории динамических систем: параметрической идентификации математических моделей и определение оптимального режима работы. Предлагаемый подход основан на использовании математической модели, описывающей эволюцию динамического процесса, и включает критерии оптимизации непосредственно в процедуру оценки параметров. В результате совместной процедуры, в которой оценка неизвестных параметров модели осуществляется одновременно с поиском управляющих воздействий, формируется субоптимальное, но практически эффективное решение управления, обеспечивающее функционирование системы в окрестности её идеального режима. Такая интеграция позволяет явно учитывать влияние управляющих воздействий на поведение системы уже на этапе параметрической идентификации в рамках единого вычислительного контура, что повышает общую согласованность и практическую применимость получаемого решения управления. Классический подход, при котором параметрическая идентификация и оптимизация управления выполняются последовательно, приводит к накоплению ошибок: неточность идентификации напрямую снижает эффективность управления, что особенно критично для нестационарных объектов, параметры которых изменяются во времени. В отличие от классического подхода совмещённая процедура объединяет эти этапы и, несмотря на увеличение вычислительной сложности, обеспечивает более устойчивые результаты. В работе получены необходимые аналитические соотношения, разработаны вычислительные алгоритмы и рассмотрены особенности практической реализации предложенного метода. Эффективность идеи демонстрируется результатами численных экспериментов и компьютерного моделирования, демонстрирующих её перспективность для решения сложных задач управления и моделирования в инженерных приложениях.

ABSTRACT

This paper presents a unified approach to the simultaneous solution of two traditionally separated problems in the theory of dynamic systems: parametric identification of mathematical models and determination of the optimal operating regime. The proposed approach is based on the use of a mathematical model that describes the evolution of a dynamic process and embeds optimization criteria directly into the parameter estimation procedure. As a result of the combined procedure, in which unknown model parameters are estimated simultaneously with the search for control actions, a suboptimal but practically efficient control solution is formed that ensures system operation in the vicinity of its ideal regime. Such integration makes it possible to explicitly account for the influence of control actions on system behaviour already at the stage of parametric identification within a unified computational framework, thereby improving the overall consistency and practical applicability of the resulting control solution. The classical approach, in which parametric identification and control optimization are performed sequentially, leads to error accumulation: identification inaccuracies directly reduce control efficiency, which is particularly critical for nonstationary objects with time-varying parameters. In contrast to the classical approach, the combined procedure integrates these stages and, despite the increased computational complexity, provides more robust results. The paper derives the necessary analytical relationships, develops computational algorithms, and discusses the practical implementation of the proposed method. The effectiveness of the approach is demonstrated through numerical experiments and computer simulations, confirming its potential for solving complex control and modelling problems in engineering applications.

Ключевые слова: динамические системы, параметрическая идентификация, оптимальный режим работы, математическое моделирование, субоптимальное решение.

Keywords: dynamic systems, parametric identification, optimal operation mode, mathematical modelling, suboptimal solution.

Введение

Современные технологические и инженерные системы характеризуются возрастающей сложностью, высокой степенью нелинейности и наличием неопределённостей, обусловленных как внешними возмущениями, так и изменением внутренних параметров объектов управления. В таких условиях обеспечение требуемого качества автоматизированного управления напрямую зависит от адекватности используемых математических моделей. Недостаточная точность модели приводит к снижению эффективности синтезируемых алгоритмов управления, ухудшению устойчивости и отклонению режимов функционирования от оптимальных.

При анализе и управлении технологическими процессами нередко применяются статистические подходы к построению моделей, эффективность которых обычно предполагает неизменность структуры динамики объекта на рассматриваемом интервале времени. Однако в условиях, описанных выше, задача выбора адекватного математической описания приобретает принципиальное значение. Модель, корректно описывающая объект в глобальном смысле, часто демонстрирует недостаточную точность в локальных областях пространства параметров.

Цель

Целью данной работы является разработка и исследование подхода, направленного на совместное решение задач параметрической идентификации и оптимизации управления динамической системой в рамках единой итерационной процедуры. Мы рассмотрим два варианта этой совмещенной процедуры: первый вариант предполагает исключение наблюдений удаленных от текущей оптимальной точки, что позволяет сосредоточить идентификацию на области, наиболее значимой для формирования оптимального режима. Второй вариант использует весь доступный массив наблюдений, при этом наблюдениям присваиваются веса в зависимости от их близости к формирующемуся оптимуму.

Дополнительной целью исследования является анализ практической эффективности предложенного подхода на основе численных экспериментов, а также сравнение получаемых стратегий управления с результатами традиционного последовательного решения задач параметрической идентификации и оптимизации. Предполагается показать, что совмещенная процедура способна приводить к существенно отличающимся и более эффективным стратегиям управления по сравнению с классическим подходом.

Постановка задачи

Рассмотрим динамическую систему или некоторый технологический процесс, текущее состояние которого $x(t) \in R^n$ в момент времени $t \in [0,T]$ определяется начальным состоянием $x_0 \in R^n$, набором неуправляемых (нерегулируемых) параметров $v \in R^m$, значения которых заданы на начальном этапе процесса, и набором управляемых (регулируемых) параметров $u \in R^r$, определенных на всем временном промежутке $[0,T]$.

Пусть эволюция динамического процесса описывается следующей задачей Коши:

$$\dot{x}(t) = g(x(t),u,v,p), x(0) = x_0 \in X_0, \quad (1)$$

где $x(t) = x(t;x_0,u,v)$ - функция, описывающая процесс соответствующий начальному состоянию x_0, фиксированным значениям неуправляемых параметров $v \in V$ и выбранным значениям управляемых параметров $u \in U$; $p \in P$ – вектор параметров математической модели; P – множество допустимых значений параметров математической модели процесса; V и U – представляют собой множества допустимых значений неуправляемых и управляемых параметров соответственно; и X_0 – множество возможных начальных состояний процесса.

Пусть функционал определенный следующим образом:

$$F(u,x_0,v,p) = \int_0^T h(x(t),u,v)dt + \Phi(x(T),u,v), \quad (2)$$

который необходимо минимизировать относительно $u \in U$, отражает качество выбранных значений управляемых параметров u в зависимости от заданного начального состояния x_0 и значений неуправляемых параметров v, где $h(\cdot)$ и $\Phi(\cdot)$ - непрерывно-дифференцируемые функции, которые определяют текущие и конечные затраты процесса соответственно.

На практике динамика системы $g(\cdot)$ не всегда известна в явном виде; В таком случае выделяется некоторый класс параметрических моделей. Идентификация конкретной функции в рамках этого класса опирается на экспериментальные данные и производится в два этапа:

1. Структурная идентификация, которая определяет вид функциональной зависимости с точностью до вектора параметров p;
2. Параметрическая идентификация, которая оценивает численные значения этих параметров [1].

Предположим, что этап структурной идентификации – выполнен, на основе априорной информации или экспертных предположений, таким образом динамика системы аппроксимируется следующим образом:

$$\dot{y}(t) = f(y(t),u,v,p), t \in [0,T], \quad (3)$$

где f – вектор-функция, параметризованная $p \in R^l$ и непрерывно-дифференцируемая по своим аргументам; $p \in P$ – вектор параметров математической модели процесса, значения которых необходимо найти на этапе параметрической идентификации. Обратим внимание, что аппроксимация (3) может не полностью отражать реальную динамику системы.

Для оценки параметров, поведение системы наблюдается при различных конфигурациях $u^i \in U$ и $v^i \in V$, при этом наблюдения могут проводиться в конкретные моменты времени $t_{i,j} \in [0,T]$:

$$x_j^i = x^i\left(t_{i,j};v^i,u^i\right), i = \overline{1,N}, j = \overline{0,L_i}, \quad (4)$$

или, к примеру, только в начальный и конечный моменты времени $t = 0$ и $t = T$:

$$x_0^i = x^i(0;v^i,u^i), x_T^i = x^i(T;v^i,u^i), i = \overline{1,N}. \quad (5)$$

Наблюдения также могут представлять собой данные временных рядов за интервалы:

$$x_j^i = x^i(t; v^i, u^i), t \in \left[t_{i,j-1}, t_{i,j}\right], i = \overline{1,N}, j = \overline{0,L_i}. (6)$$

Каждому наблюдению соответствует некоторый весовой коэффициент $\sigma_i \in [0,1]$, отражающий надежность данных. Используя такие данные, можно представить задачу параметрической идентификации как задачу минимизации функционала, к примеру, методом наименьших квадратов. В зависимости от формата наблюдения, функционал принимает один из следующих видов [2]:

1. При наблюдениях вида (4):

$$S_1(p) = \sum_{i=1}^{N}\sum_{j=1}^{L_i}\sigma_i\left\|y^i\left(t_{i,j}\right) - x_j^i\right\|_{R^n}^2 + \varepsilon\|p\|_{R^l}^2; \quad (7)$$

2. При наблюдениях вида (5):

$$S_2(p) = \sum_{i=1}^{N}\sigma_i\left\|y^i(T) - x_T^i\right\|_{R^n}^2 + \varepsilon\|p\|_{R^l}^2; (8)$$

3. При наблюдениях вида (6):

$$S_3(p) = \sum_{i=1}^{N}\sum_{j=1}^{L_i}\sigma_i\int_{t_{i,j-1}}^{t_{i,j}}\left\|y^i(t) - x_j^i(t)\right\|_{R^n}^2 dt + \varepsilon\|p\|_{R^l}^2. \quad (9)$$

Здесь $y^i(t) = y(t; v^i, u^i, p)$ – решение (3) при входных параметрах v^i, u^i, p и начальном условии $y^i(0) = x_0^i$; $\varepsilon\|p\|_{R^l}^2$ – член регуляризации, обеспечивающий численную устойчивость и устраняющий некорректности в оценке [3,4].

Следовательно, построение модели принятия решений для управления такими системами включает два основных этапа:

1. Параметрическая идентификация путем минимизации одного из функционалов $S_1(p)$, $S_2(p)$ или $S_3(p)$ на основе имеющихся данных;

2. Решение задачи оптимального управления (2) и (3) для фиксированной модели, определённой идентифицированными параметрами путем минимизации функционала $F(u)$ при заданном начальном состоянии $x_0 \in X_0$ и векторе неуправляемых параметров $v \in V$.

Численное решение

Как задача параметрической идентификации (3) – (9), так и задача оптимального управления (2) и (3), относятся к категории параметрических задач оптимального управления. Таким образом, для их решения могут быть использованы устоявшиеся численной методы оптимизации, в частности, эффективные методы первого порядка. К примеру, когда множества допустимых значений параметров P и U – имеют простые геометрические структуры (например, сфера, параллелепипед), то очень эффективным является метод проекция градиента [5,6,7].

Градиентная параметрическая идентификация

Для оценки вектора параметров p мы используем следующий итерационный процесс:

$$p^{(k+1)} = Proj_p(p^{(k)} - \alpha_k\nabla S(p^{(k)})) \quad k = 0,1,2, ..., \quad (10)$$

где $Proj_p(\cdot)$ – обозначает проекцию на допустимую область P; $\alpha_k -$ шаг минимизации.

Градиент $\nabla S\left(p^{(k)}\right)$ вычисляется по формуле:

$$\nabla S\left(p^{(k)}\right) = 2\varepsilon p^{(k)} - \sum_{i=1}^{N}\int_0^T\frac{\partial f(y^i(t),u^i,v^i,p^{(k)})}{\partial p}\psi^i(t)dt, \quad (11)$$

где каждая $y^i(t)$ – есть решение (3) с начальным условием $y^i(0) = x_0^i$; $\psi^i(t)$ -удовлетворяет сопряженной задаче, вид которой зависит от вида наблюдений и функционала. К примеру для наблюдений вида (4) или (5) и для функционала (7) сопряженная задача выглядит следующим образом:

$$\dot{\psi^i}(t) = -\left[\frac{\partial f(y^i(t),u^i,v^i,p)}{\partial y}\right]^T\psi^i(t) + 2\sigma_i\sum_{j=1}^{L_i}\left[y^i(t) - x_j^i\right]\delta\left(t - t_{i,j}\right), t\epsilon(0,T], \quad (12)$$

при условии:

$$\psi^i(T) = 0, \quad (13)$$

где $\delta(\cdot)$ – функция Дирака; T – знак транспонирования матрицы. Для наблюдений вида (6) и для функционала (9) сопряженная задача выглядит так:

$$\dot{\psi^i}(t) = -\left[\frac{\partial f(y^i(t),u^i,v^i,p)}{\partial y}\right]^T\psi^i(t) + 2\sigma_i\sum_{j=1}^{L_i}\left[y^i(t) - x_j^i(t)\right]\chi_j^i(t), \quad t\epsilon(0,T], \quad (14)$$

при том же условии, что и (13), где χ_j^i – функция Хэвисайда, определенная как:

$$\chi_j^i(t) = \begin{cases}1, t \in \cup_{j=1}^{N}\left[t_{i,j-1}, t_{i,j}\right] \cap [t,T]\\ 0, t \notin \cup_{j=1}^{N}\left[t_{i,j-1}, t_{i,j}\right] \cap [t,T]\end{cases}. (15)$$

Описанные выше соотношения могут быть получены либо с применением метода вариаций оптимизируемых параметров, либо посредством обращения к известным результатам из работ [5, 6, 8, 9], поскольку задачи (3)–(9) являются частным случаем общей постановки задачи оптимального управления.

Градиентный метод оптимального управления

После процедуры параметрической идентификации, получив оценки параметров системы p, опишем процедуру решения задачи оптимального управления. Вектор оптимального управления u может быть найден аналогичным методом проекции градиента:

$$u^{(k+1)} = Proj_u\left(u^{(k)} - \alpha_k\nabla F\left(u^{(k)}\right)\right) \quad k = 0,1,2, ..., \quad (16)$$

где

$$\nabla F\left(u^{(k)}\right) = \int_0^T\left(-\frac{\partial h\left(y^{(k)}(t),u^{(k)},\bar{v},p\right)}{\partial u} + \left[\frac{\partial f\left(y^{(k)}(t),u^{(k)},\bar{v},p\right)}{\partial u}\right]^T\varphi^{(k)}(t)\right)dt + + \frac{\partial\Phi\left(y^{(k)}(T),u^{(k)},\bar{v}\right)}{\partial u} \quad (17)$$

Тут $y^{(k)}(t) = y\left(t; u^{(k)}, \bar{v}, p\right)$ – решение, полученное при текущем управлении $u^{(k)}$ при начальном условии $y^{(k)}(0) = \overline{x_0}$; $\varphi^k(t) = \varphi^k\left(t; \overline{x_0}, u^{(k)}, \bar{v}\right)$ – решение сопряженной задачи:

$$\dot{\varphi^k}(t) = \frac{\partial h\left(y^{(k)}(t), u^{(k)}, \bar{v}, p\right)}{\partial y} - \left[\frac{\partial f\left(y^{(k)}(t),u^{(k)},\bar{v},p\right)}{\partial y}\right]^T\varphi^k(t), t\epsilon[0,T], \quad (18)$$

при условии:

$$\varphi^k(T) = -\frac{\partial \Phi(y^{(k)}(T), u^{(k)}, \bar{v})}{\partial y}. \quad (19)$$

Ключевым недостатком классического двухэтапного подхода является его зависимость от единственной оценки параметров, основанной на имеющихся наблюдениях. Кроме того, при аппроксимации функции $g(\cdot)$ часто используются линейные или квадратичные приближения, поэтому оценочные значения траектории могут существенно отличаться от реальной траектории, особенно когда начальные состояния или параметры управления значительно изменяются в процессе наблюдений. Для решения этой проблемы предлагается единый алгоритм, объединяющий процедуры параметрической идентификации и оптимизации управления. В частности, после каждого шага оптимизации управления (16) параметры pбудут повторно идентифицироваться на основе данных, взвешенных по их близости к текущему контексту оптимума. В этом случае, каждому наблюдению i назначаются веса $\phi^i(\overline{x_0}, \bar{v}, u^{(k)}), i = 1,2, \dots, N,$ обратно пропорциональные расстоянию между наблюдаемыми параметрами процесса (x_0^i, v^i, u^i) и значениями $(\overline{x_0}, \bar{v}, u^{(k)})$. В таком случае функционал (7) на k – ой итерации принимает вид:

$$S_1^k(p; \overline{x_0}, \bar{v}, u^{(k)}) = \sum_{i=1}^N \phi^i(\overline{x_0}, \bar{v}, u^{(k)}) \sum_{j=1}^{L_i} \sigma_i \| y^i(t_{i,j}; v^i, u^i, p) - x_j^i \|_{R^n}^2 + + \varepsilon \|p\|_{R^l}^2, \quad (20)$$

и в случае, когда $L_i = 1$ и $t_{i,L_i} = T$, функционал (8) принимает вид:

$$S_2^k(p; \overline{x_0}, \bar{v}, u^{(k)}) = \sum_{i=1}^N \phi^i(\overline{x_0}, \bar{v}, u^{(k)}) \sigma_i \| y^i(T; v^i, u^i, p) - x_T^i \|_{R^n}^2 + + \varepsilon \|p\|_{R^l}^2. \quad (21)$$

Таким же образом изменяется и функционал (9). Такое локальное взвешивание обеспечивает, что оцениваемые параметры p лучше отражают динамику, соответствующую текущей точке управления. В качестве весовых функций может использоваться функция следующего вида:

$$\phi^i(\overline{x_0}, \bar{v}, u^{(k)}) = \phi_x^i(\overline{x_0}) + \phi_v^i(\bar{v}) + \phi_u^i(u^{(k)}), \quad (22)$$

$$\phi_x^i(\overline{x_0}) = e^{-\lambda_1 \| x_0^i - \overline{x_0} \|}; \quad \phi_v^i(\bar{v}) = e^{-\lambda_2 \| v^i - \bar{v} \|}; \quad \phi_u^i(u^{(k)}) = e^{-\lambda_3 \| u^i - u^{(k)} \|}.$$

Тут $\lambda_1, \lambda_2, \lambda_3$ – постоянные. При этом функции $\phi_x^i(\overline{x_0})$, $\phi_v^i(\bar{v})$ – остаются неизменными как в процессе параметрической идентификации, так и в процессе оптимизации управления. Они становятся известными после того, как задаются начальное состояние $\overline{x_0}$ и неуправляемые параметры $\bar{v}$. А параметры процесса p будут изменяться в ходе итерационного процесса оптимизации управления (16) в силу изменения значений функции $\phi_u^i(u^{(k)}), i = 1,2, \dots, N, k = 1,2, \dots$.

Замечание 1. В качестве альтернативы аддитивной форме весовой функции (22) можно использовать мультипликативную формулу:

$$\phi^i(\overline{x_0}, \bar{v}, u^{(k)}) = \phi_x^i(\overline{x_0}) * \phi_v^i(\bar{v}) * \phi_u^i(u^{(k)}),$$

либо любую другую функцию, монотонно убывающую по мере увеличения значений разностей $\|x_0^i - \overline{x_0}\|$, $\|v^i - \bar{v}\|$, $\|u^i - u^{(k)}\|$.

Замечание 2. Альтернативная реализация стратегии совместного решения задачи параметрической идентификации и оптимизации управления заключается в исключении наблюдений, удалённых от текущих значений $(\overline{x_0}, \bar{v}, u^{(k)})$. В частности, на каждой итерации оптимизации управления (16) сохраняются только те наблюдения, которые находятся в пределах заранее заданного порога близости. В этом варианте реализации совместного решения весовые функции $\phi^i(\cdot)$ не используются, а параметрическая идентификация выполняется только на сокращённом наборе наблюдений.

В предлагаемой совмещенной модели задачи параметрической идентификации и оптимизации управления объединяются в единую задачу в следующей форме:

$$F(u; \overline{x_0}, \bar{v}, \arg\min_{p \in P} S(p; \overline{x_0}, \bar{v}, u)) \to \min_{u \in U}, \quad (23)$$

или

$$F(u; \overline{x_0}, \bar{v}, p^*(u)) \to \min_{u \in U}, \; p^*(u) = \arg\min_{p \in P} S(p; \overline{x_0}, \bar{v}, u). \quad (24)$$

Тут $F(\cdot)$ и $S(\cdot)$ – обозначают функционалы, аналогичные тем, которые были определены в (2), (20) и (21), в то время как значения $(\overline{x_0}, \bar{v})$ – известны. Пара точек $(u^*, p^*(u^*))$ – есть решение задачи (23) или (24), к тому же она отражает тот факт, что в процессе параметрической идентификации модели большое значение придается наблюдениям в окрестности u^*. Таким образом идентифицированная математическая модель становится «локально оптимальной» в окрестности реализуемой стратегии управления.

Для реализации описанной выше стратегии предлагается следующий алгоритм:

1. **Инициализация.** Для известных значений начального состояния $\overline{x_0}$ и неуправляемых параметров $\bar{v}$ для всех наблюдений вычислить значения функций $\phi_x^i(\overline{x_0})$ и $\phi_v^i(\bar{v})$. Установить значения $k = 0$ и $\phi_u^i(u^{(k)}) = 1, i = 1,2, \dots, N$.
2. **Оценка параметров.** Используя выражения (10) – (15), выполнить процедуру параметрической идентификации и получить начальную оценку параметров $p^{(k)*}$.
3. **Оптимизация управления.** Применить итерационные формулы (16) – (19) для получения значений вектора управляемых параметров $u^{(k)*}$.
4. **Уточнение.** Используя один шаг итерационных формул (16) – (19), обновить значения вектора управляемых параметров до $u^{(k+1)*}$, затем пересчитать значения весовой функции $\phi_u^i(u^{(k+1)})$ и переоценить параметры $p^{(k+1)*}$.
5. **Проверка сходимости.** Если $\|u^{(k+1)*} - u^{(k)*}\| > \varepsilon$, то установить $k = k + 1$ и вернуться к шагу 4. Иначе завершить алгоритм, так как достигнута требуемая точность $\varepsilon > 0$.

При реализации данного алгоритма в какой-либо системе автоматизированного управления не

требуется сохранять данные математической модели процесса. Вместо этого можно сохранять данные «информационной модели» процесса, состоящую из:

1. Структуры дифференциальных уравнений (3);
2. Функционала (2);
3. Наблюдений (4), (5) или (6).

Очевидно, что предлагаемый подход требует больших вычислительных затрат по сравнению с классическим двухэтапным подходом. Однако он учитывает специфические значения начальных состояний и неуправляемых параметров в процессе оптимизации управления. В результате вышеописанной процедуры модель становится локально оптимальной в окрестности точки $u^* \in U$.

Результаты численных экспериментов. В качестве тестовой системы для исследования эффективности предложенного совмещенного подхода рассмотрим модифицированную модель Лотки-Вольтерры (хищник-жертва) с управлением. Пусть реальное поведение системы описывается следующей системой дифференциальных уравнений:

$$\begin{cases} ax_1\left(1-\frac{x_1}{5}\right) - 0.6\frac{x_1x_2}{1+0.1x_1} - u_1x_1 = \dot{x}_1(t) \\ -bx_2 + 0.4\frac{x_1x_2}{1+0.1x_1} - u_2x_2 = \dot{x}_2(t) \end{cases}, \quad (25)$$

где $x_1(t)$ – плотность популяции жертв; $x_2(t)$ – плотность популяции хищников; $a = 1.5 + 0.3v$ – коэффициент рождаемости жертв; $b = 0.8 - 0.2v$ – коэффициент смертности хищников; $v \in [-0.5,1]$ – неуправляемый параметр среды, отражающий внешние условия, влияющие на коэффициент рождаемости жертв a и коэффициент смертности хищников b; $u = (u_1, u_2)$ - вектор управляемых параметров, где u_1 и u_2 - доли плотностей популяций жертв и хищников соответственно, изымаемых в единицу времени; $t \in (0, T]$; $T = 1$ – длительность процесса; и $x_0 \in X_0 = \{x(0): 1.5 \le x_1(0) \le 2.5, 1.0 \le x_2(0) \le 1.8\}$.

Задача заключается в том, чтобы найти вектор управляемых параметров u, который минимизирует расстояние между значениями $x(T)$ и заданным значением $x_T = (2{,}045; 1.187)$, которое выражено в виде следующего функционала:

$$F(u; x_0, v, p) = \|x(T; x_0, u, v) - x_T\|^2_{R^2} \to \min_{u \in R^2}. \quad (26)$$

Численным решением задачи при значениях $x(0) = (2{,}1.5)$ и $v = 0.5$ является вектор $u^* = (0.3{,}0.2)$, который минимизирует функционал (25).

Теперь, предположим, что точный вид реального процесса неизвестен и для моделирования реального сценария, предположим, что процесс аппроксимируется следующей системой дифференциальных уравнений:

$$\begin{cases} (a - p_1y_2 - u_1)y_1 = \dot{y}_1(t) \\ (-b + p_2y_1 - u_2)y_2 = \dot{y}_2(t) \end{cases}, \quad (27)$$

где $p = (p_1, p_2) \in R^2$ - вектор неизвестных параметров.

Пусть наблюдения за состоянием системы проводятся $N = 12$ раз при случайно выбранных значениях параметров $x^i(0) \in X_0$, $u^i \in U$ и $v^i \in V$, $i = \overline{1, N}$, равномерно распределенных в соответствующих допустимых множествах:

$$X_0 = \{x(0): 1.5 \le x_1(0) \le 2.5, 1.0 \le x_2(0) \le 1.8\},$$
$$V = [-0.5, 1],$$
$$U = \{u = (u_1, u_2): 0.1 \le u_1 \le 0.5, 0.05 \le u_2 \le 0.35\}.$$

Множества X_0, V, U выбраны как окрестности целевого режима $(x_0, v, u^*) = ((2.0, 1.5), 0.5, (0.3{,}0.2))$. Положительность диапазонов множеств X_0 и U соответствует физическому смыслу задачи: x_1, x_2 обозначают плотности популяций, а u_1, u_2 – доли плотностей популяций, изымаемых в единицу времени. Для воспроизводимости численных экспериментов фиксируется начальное значение генератора псевдослучайных чисел.

Для каждого наблюдения регистрируется конечное состояние x_T^i реальной системы в момент времени $T = 1$. Параметрическая идентификация данной модели приводит к минимизации функционала:

$$S(p) = \sum_{i=1}^{N} \sigma_i \left\| y^i(T; v^i, u^i, p) - x_T^i \right\|^2_{R^2} + \varepsilon \|p\|^2_{R^2},$$

где все наблюдения имеют одинаковый вес - $\sigma_i = 1$, а $\varepsilon = 10^{-4}$ – параметр регуляризации. При условии, что на параметры p не наложены ограничения ($P = R^2$), итерационный процесс метода проекции градиента вырождается в градиентный спуск:

$$p^{(k+1)} = p^{(k)} - \alpha_k \nabla S\left(p^{(k)}\right),$$

градиент вычисляется с помощью решений прямых и сопряженных задач. Соответствующая сопряженная задача для каждого наблюдения i определена аналитически и решается с использованием следующего условия:

$$\psi^i(T) = 2\left[y^i\left(T; v^i, u^i, p^{(k)}\right) - x_T^i\right].$$

Для определения вектора оптимального управления u^i при известных значениях начального состояния и неуправляемого параметра v, мы применяем процедуру градиентного спуска, основанную на формулах, выведенных в предыдущем разделе. Соответствующая сопряженная задача также решается численно для вычисления значения $\nabla F(u^{(k)})$.

Сравнение подходов. Используя классический двухэтапный подход (этап 1 – параметрическая идентификация, этап 2 – оптимизация управления), были найдены значения параметров $p^* = (1.0320, 0.3385)$ с соответствующими оптимальными значениями управляемых параметров $u^* = (0.2491{,}0.1999)$ с результирующими значениями функционалов $S(p^*) \approx 0.638$, $F(u^*) \approx 6.03 * 10^{-3}$. Используя предложенный совмещенный подход, в рамках которого параметрическая идентификация и оптимизация управления проводятся в едином вычислительном контуре, удалось получить значительно более качественные результаты. Вычисленные значения параметров $p^* = (1.0252, 0.3385)$ и $u^* = (0.2582, 0.2002)$ с результирующими значениями функционалов $S(p^*) \approx 1.07$, $F(u^*) \approx 4.15 * 10^{-3}$. Для вычисления значений весовых функций

были использованы значения постоянных: $\lambda_1 = \lambda_2 = 1$ и $\lambda_3 = 15$.

Заметим, что значение функционала идентификации $S(p^*)$ в совмещённом подходе оказывается больше, чем в двухэтапном. Это закономерно: функционал $S(p)$ представляет собой сумму квадратов отклонений предсказаний модели от наблюдённых значений, причём в совмещённом подходе эта сумма вычисляется с весовыми коэффициентами, тогда как в двухэтапном подходе все наблюдения имеют равный вес. Совмещённая процедура не стремится подогнать модель равномерно по всем наблюдениям, а делает это локально, придавая больший вес наблюдениям из окрестности оптимального режима. Прямое сравнение значений S в двух подходах методологически некорректно — это значения разных функционалов, минимизируемых до своих собственных минимумов.

Объективным критерием сравнения подходов является значение функционала управления $F(u^*)$, вычисленного при подстановке найденного u^* в реальный процесс согласно формуле (26). Совмещённый подход даёт $F(u^*) \approx 4.15 * 10^{-3}$ против $F(u^*) \approx 6.03 * 10^{-3}$ для двухэтапного подхода - улучшение качества управления реальным процессом в 1.45 раза.

Дополнительным подтверждением преимущества совмещённого подхода является сравнение полученных оптимальных управлений с истинным оптимальным значением $u^* = (0.3,0.2)$, известным по построению тестовой задачи. Расстояния до истинного оптимума: для двухэтапного подхода - 0.0509; для совмещённого подхода - 0.0418. Управление, найденное совмещённым методом, оказывается ближе к реально оптимальному вектору, чем управление, полученное двухэтапным методом.

Данный численный эксперимент подчёркивает явное преимущество совмещённой процедуры по сравнению с классической двухэтапной процедурой: она позволяет получать управление, обеспечивающее более высокое качество функционирования реального процесса в окрестности целевого режима.

Анализ чувствительности по параметрам весовых функций. Эффективность совмещенного подхода существенно зависит от выбора параметров $\lambda_1, \lambda_2, \lambda_3$ в весовых функциях $\phi^i = \phi_x^i + \phi_v^i + \phi_u^i$. С целью изучения этой зависимости проведены серии вычислительных экспериментов, в каждом из которых варьируется один из параметров λ_j при фиксированных остальных. Качество найденного управления оценивается по значению функционала $F(u^*)$ согласно формуле (26). Базовое значение для двухэтапного подхода составляет $F(u^*) \approx 6.03 * 10^{-3}$.

В таблице 1 приведены результаты варьирования параметра λ_3 (вес близости по управлению) при фиксированных $\lambda_1 = \lambda_2 = 1$.

Таблица 1.

Влияние λ_3 на качество управления

λ_3	0.5	1.0	2.0	5.0	10.0	15.0	25.0
$F(u^*) * 10^{-3}$	5.57	5.46	5.26	4.81	4.36	4.15	4.05

Из таблицы 1 видно, что увеличение λ_3 от 0.5 до 25 приводит к монотонному улучшению качества управления – от $F = 5.57 * 10^{-3}$ до $F = 4.05 * 10^{-3}$. При всех значениях λ_3 совмещенный подход превосходит двухэтапный.

В таблице 2 приведены результаты варьирования параметра λ_1 (вес близости по начальному состоянию) при фиксированных $\lambda_2 = 1, \lambda_3 = 15$.

Таблица 2.

Влияние λ_1 на качество управления

λ_1	0.5	1.0	2.0	5.0	10.0	15.0	25.0
$F(u^*) * 10^{-3}$	4.50	4.16	3.71	3.41	3.71	3.90	4.00

Зависимость $F(u^*)$ от λ_1 имеет выраженный U-образный характер с минимумом при $\lambda_1 = 5$. Слишком малые значения λ_1 ослабляют локализующее действие весовой функции ϕ_x^i, тогда как слишком большие приводят к «вырождению» выборки.

В таблице 3 приведены результаты варьирования параметра λ_2 (вес близости по неуправляемому параметру) при фиксированных $\lambda_1 = 1, \lambda_3 = 15$.

Таблица 3.

Влияние λ_2 на качество управления

λ_2	0.5	1.0	2.0	5.0	10.0	15.0	25.0
$F(u^*) * 10^{-3}$	4.25	4.16	3.81	2.71	1.94	1.79	1.95

Зависимость $F(u^*)$ от λ_2 также имеет U-образный характер с минимумом при $\lambda_2 = 15$, причем изменение λ_2 оказывает наибольшее влияние на результат среди всех трех параметров. При оптимальном значении $\lambda_2 = 15$ функционал $F(u^*) = 1.79 * 10^{-3}$, что соответствует улучшению в 3.4 раза по сравнению с двухэтапным подходом.

Выводы из анализа чувствительности. Проведенный анализ позволяет сделать следующие выводы. Во-первых, по всем трем параметрам $\lambda_1, \lambda_2, \lambda_3$ совмещенный подход демонстрирует устойчивое преимущество над двухэтапным во всем исследованном диапазоне значений. Во-вторых, по параметрам λ_1 и λ_2 зависимость $F(u^*)$

имеет U-образный характер с выраженным минимумом, что указывает на существование оптимального уровня локализации выборки. В-третьих, наибольший эффект достигается при варьировании параметра λ_2, что может быть связано с большим влиянием неуправляемого параметра v на динамику рассматриваемой системы Лотки-Вольтерры.

Полученные результаты указывают на перспективное направление дальнейших исследований – разработку методики адаптивного выбора параметров λ_j в зависимости от структуры конкретной задачи и характеристик имеющейся выборки наблюдений.

Заключение. В данной работе была представлена совмещенная процедура, которая одновременно решает задачи параметрической идентификации и оптимизации динамических процессов. В отличие от традиционных двухэтапных методов, которые рассматривают эти задачи, как отдельные, независимые друг от друга задачи, предложенная совмещенная процедура объединяет их в едином вычислительном контуре. Это позволяет получить субоптимальное решение, точно отражающее функционирование системы в окрестности её целевого режима.

Существенное достоинство метода состоит в том, что при идентификации параметров приоритет отдается тем экспериментальным данным, которые получены в условиях, наиболее близких к текущему режиму функционирования системы и реализуемому управлению. Такая схема приводит к построению модели, более адекватной реальной ситуации, в которой осуществляется синтез и реализация управляющих воздействий.

Несмотря на возрастание вычислительной нагрузки, обусловленной повторной идентификацией параметров на каждом шаге оптимизации управления, проведённые численные эксперименты подтверждают эффективность предлагаемого подхода. Важно подчеркнуть, что стратегии управления, синтезированные в рамках данной процедуры, могут заметно отличаться от решений, полученных при классическом двухэтапном подходе; тем не менее при проверке на моделях с учетом истинной динамики системы они демонстрируют более высокую точность и эффективность.

Литература

1. П. Эйкхофф. Основы идентификации систем управления. – М.: Мир, 1975. - 495 с.
2. Х. Мотульский, А. Христопулос. Подгонка моделей к биологическим данным с использованием линейной и нелинейной регрессии: практическое руководство по аппроксимации кривых. Оксфорд: Издательство Оксфордского университета, 2023.
3. А. Н. Тихонов, В. А. Арсенин. Методы решения некорректных задач. – М.: Наука, 1979. - 284 с.
4. А. А. Самарский, П. Н. Вабищевич. Численные методы решения обратных задач математической физики: Учебное пособие. Изд. 3-е. – М.: Издательство ЛКИ, 2009. - 480 с.
5. Ю. Г. Евтушенко. Методы решения экстремальных задач и их применение в системах оптимизации. – М.: Наука, 1982. - 264 с.
6. Ф. П. Васильев. Методы оптимизации. – М.: Факториал Пресс, 2002. – 824 с.
7. Дж. Носедал, С. Дж. Райт. Численная оптимизация. Нью-Йорк: Springer, 2006.
8. Р. Габасов, Ф. М. Кирилова. Принцип максимума в теории оптимального управления. – Минск: Наука и техника, 1974. – 272 с.
9. В. Лакшмикантам, Метод вариации параметров для динамических систем. Лондон: Routledge, 2019.

ОСОБЛИВОСТІ ПЕРЕДАВАННЯ КОРИСТУВАЦЬКОГО ТРАФІКУ 5G NR ЧЕРЕЗ EPC У NSA-АРХІТЕКТУРІ ЗА УМОВ ЧАСТКОВИХ ВІДМОВ ЕЛЕКТРОЖИВЛЕННЯ

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FEATURES OF TRANSMISSION OF 5G NR USER TRAFFIC VIA EPC IN NSA ARCHITECTURE UNDER CONDITIONS OF PARTIAL POWER FAILURES

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АНОТАЦІЯ

У статті досліджено особливості передавання користувацького трафіку 5G NR у неповністю автономній архітектурі 5G NSA, де NR-радіодоступ функціонує спільно з LTE-інфраструктурою та EPC [1, с. 18–22; 2, с. 54–61]. Показано, що в NSA некоректно трактувати NR як окрему систему пакетної комутації 5G, оскільки площину користувача реалізує EPC, а LTE eNB виконує роль головного вузла в процедурах керування та взаємодії з ядром мережі [1, с. 18–22; 3, с. 14–19]. Уточнено роль PDCP у варіанті EN-DC Option 3x, описано значення S1-U та GTP-U-тунелювання для передавання користувацьких даних, а також проаналізовано вплив часткових відмов електроживлення на роботу радіодоступності, транспортної мережі та механізмів маршрутизації користувацького трафіку [1, с. 29–37; 4, с. 1–3]. Показано, що X2 стає критичним насамперед за деградованих транспортних умов, а перебої з електропостачанням доцільно використовувати як аналітичну абстракцію для опису енергетично зумовленої деградації сервісу [1, с. 24–29; 5, с. 1–6; 8, с. 1–5].

ABSTRACT

The article investigates the features of 5G NR user traffic transmission in a non-standalone architecture (5G NSA), where NR radio availability functions together with LTE infrastructure and EPC [1, pp. 18–22; 2, pp. 54–61]. It is shown that in NSA it is incorrect to treat NR as a separate 5G packet switching system, since the user plane is implemented via EPC, and the LTE eNB performs the role of a master node in control procedures and interaction with the network core [1, pp. 18–22; 3, pp. 14–19]. The role of PDCP in the EN-DC Option 3x variant is clarified, the significance of S1-U and GTP-U tunneling for user data transmission is described, and the impact of partial power failures on the operation of radio availability, transport network, and user-plane forwarding mechanisms is analyzed [1, pp. 29–37; 4, pp. 1–3]. It is shown that X2 becomes critical primarily under degraded transport conditions, and power outages are useful as an analytical abstraction to describe energy-related service degradation [1, pp. 24–29; 5, pp. 1–6; 8, pp. 1–5].

Ключові слова: 5G NSA, EPC, EN-DC, користувацький трафік, S1-U, GTP-U, PDCP, LTE, 5G NR, перебої в електропостачанні.

Keywords: 5G NSA, EPC, EN-DC, user plane, S1-U, GTP-U, PDCP, LTE, 5G NR, power outages.

Наукова новизна.

Наукова новизна полягає в тому, що уточнено межі застосування термінів NSA, EPC-based user-plane forwarding, S1-U, X2-U та PDCP у варіанті EN-DC Option 3x, а також запропоновано розглядати перебої в електропостачанні як аналітичну абстракцію для опису енергетично зумовленої деградації сервісу.

Постановка проблеми

Переважна більшість перших комерційних розгортань 5G виконувалася у форматі NSA, коли мережа NR вводилася поверх уже наявної LTE/EPC-інфраструктури. Такий підхід забезпечив можливість швидкого запуску 5G-сервісів без одномоментного переходу до 5G, використовуючи LTE як опорний шар керування та покриття [1, с. 18–22; 2, с. 54–61]. У цьому контексті технічно точніше говорити не про «комутацію пакетів 5G у мережах 4G», а про передавання користувацького трафіку

5G NR через EPC у межах NSA-архітектури [1, с. 18–22; 3, с. 14–19].

Аналіз останніх досліджень і публікацій

Архітектурні основи EN-DC, ролі EPC, типи каналів та загальна логіка мультиз'єднань детально описані у специфікаціях 3GPP TS 37.340 і 3GPP TS 38.300 [1, с. 18–37; 2, с. 54–84]. Технічні аспекти розділення каналів, поведінки PDCP та об'єднання потоків практично розкриті в технічних оглядах і пояснювальних матеріалах, що узгоджуються зі специфікаціями [4, с. 1–4; 6, с. 1–4]. Питання впливу транспортної мережі розглядаються у профільних дослідженнях щодо затримки S1–U і втрати пакетів, а енергетична стійкість мереж — у роботах про деградацію сервісу в умовах часткової відсутності електроживлення та стійкість мережі [5, с. 1–6; 8, с. 1–5; 9, с. 1–4; 10, с. 1–4].

Мета статті

Метою статті є уточнення архітектурних і протокольних особливостей передавання користувацького трафіку 5G NR через EPC в NSA-архітектурі за умов часткового відсутності електроживлення, а також формування практичних рекомендацій щодо підвищення стійкості передавання користувацького трафіку в операторських мережах.

Основний матеріал

У 3GPP-архітектурі EN-DC з EPC користувацьке обладнання одночасно підключається до eNB як головного вузла та до en-gNB як вторинного вузла, тоді як ядро мережі залишається EPC [1, с. 18–22; 2, с. 54–61]. Типова архітектура EN-DC, що використовується в NSA-розгортаннях, наведена на рис. 1. У межах EN-DC розрізняють MCG-канал, SCG-канал і розділення каналів, що визначають спосіб проходження користувацьких даних між EPC, головним вузлом, вторинним вузлом та UE [1, с. 29–37; 4, с. 1–3]. Саме архітектура каналів, а не окрема «комутація 5G», є коректною моделлю опису користувацького трафіку в NSA [1, с. 18–22].

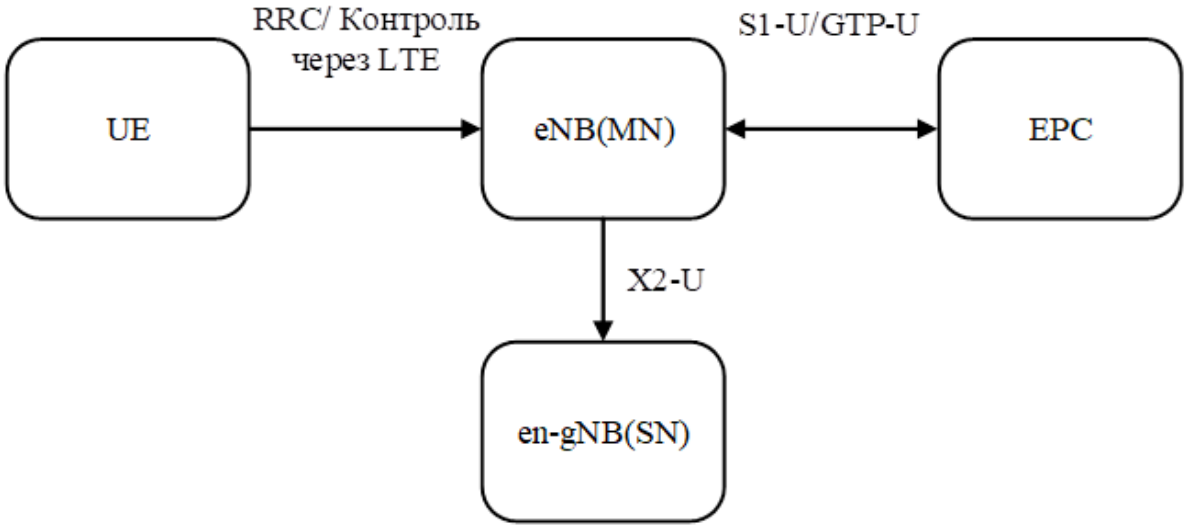

Рисунок 1 – Архітектура EN-DC (MeNB–SgNB–UE, інтерфейс X2)

Ключовим компонентом площини користувача у NSA є EPC, який забезпечує управління каналами, маршрутизацію та тунелювання користувацьких даних [1, с. 18–22; 2, с. 54–61]. Для повного технічного опису необхідно чітко враховувати інтерфейс S1-U та механізм GTP-U, оскільки саме вони формують тунельну основу доставлення пакетів між вузлами радіодоступу та ядром мережі [1, с. 18–22; 1, с. 29–37]. У типовому варіанті Option 3x трафік до вторинного вузла доставляється через MeNB за X2-U, а не через прямий кінцевий вузол S1-U в en-gNB [1, с. 18–22; 6, с. 1–4].

PDCP у цій архітектурі виконує нумерацію пакетів, перерозподіл, видалення дублікатів, шифрування та інші функції узгодження потоків, але не здійснює ретрансляції, яка належить до RLC/MAC-рівнів [1, с. 29–37; 4, с. 1–3]. Тому коректніше писати про адаптацію механізмів перерозподілу та контроль дублювання на PDCP-рівні, а не про повторні передачі на PDCP [1, с. 29–37].

Інтерфейс X2 є значущим для роботи EN-DC, однак його не слід абсолютизувати як головне вузьке місце мережі за будь-яких умов [1, с. 24–29]. У штатних операторських мережах, що працюють поверх контрольованої оптичної/MPLS-інфраструктури, затримки X2 зазвичай перебувають у межах, сумісних з нормальною роботою EN-DC [5, с. 1–6]. Критичним X2 стає насамперед у разі деградації транспорту, зокрема під час аварій електроживлення, коли порушується робота проміжних вузлів або виникає потреба в обхідній маршрутизації [5, с. 1–6; 7, с. 1–3].

За умов часткових відмов електроживлення оператори зазвичай переходять до енергозберігаючого режиму функціонування інфраструктури [7, с. 1–3; 8, с. 1–5]. У першу чергу підтримується базове LTE-покриття як опорний шар NSA, тоді як енергоємні NR-конфігурації можуть працювати у зниженому режимі або тимчасово вимикатися [2, с. 54–61; 7, с. 1–3]. Наслідком стає асиметрична доступність ресурсів LTE і NR, за якої площина користувача змінює конфігурацію без обов'язкового розриву EPC-сесії [1, с. 29–37]. Для абонента це проявляється у зниженні пропускної здатності, зростанні

затримки, нестабільності швидкості та короткочасних втратах пакетів у моменти переходу між каналами [1, с. 29–37; 5, с. 1–6].

Порівняльні характеристики LTE та 5G NR в умовах обмеженого електроживлення наведено в табл. 1.

Таблиця 1

Порівняння LTE та 5G NR при енергетичних обмеженнях

Стан	LTE	NR	Площина користувача
Штатний режим	повний	повний	Основане на EPC перенаправлення через LTE/NR
Часткова відмова живлення	збережено пріоритетно	частково обмежено	деградація до LTE-орієнтованої передачі
Деградація транспорту	залежить від маршруту	залежить від маршруту	можливі втрати пакетів, затримка, джитер
Відмова вторинного вузла	збережено	втрачено	трафік іде через MCG/LTE

Як видно з табл. 1 LTE має вищу енергетичну стійкість і відіграє роль опорної технології в NSA-архітектурі.

Твердження про те, що QoS «втрачається», є некоректним [1, с. 18–22; 2, с. 54–61]. QoS-модель логічно зберігається в межах EPC і канальної архітектури, однак фактичні показники обслуговування можуть погіршуватися через перевантаження радіосегмента, втрату NR-компоненти, втрату пакетів, затримку перенаправлення або зростання джитер [1, с. 29–37; 5, с. 1–6]. Таким чином, мова має йти не про втрату QoS як такої, а про погіршення практичної реалізації параметрів якості в умовах її деградації [1, с. 18–22].

Окремо слід зазначити, що концепція часткової відмови електроживлення використовується тут як аналітична абстракція, а не як нормативний термін 3GPP [8, с. 1–5]. Вона корисна для опису ситуацій, коли енергетичні обмеження вузлів або пристроїв фактично еквівалентні відмові каналу з погляду доступної якості обслуговування [8, с. 1–5].

Висновки

Проведений аналіз показав, що для неповністю автономної архітектури технічно некоректно використовувати формулювання про окрему «комутацію пакетів 5G у мережах 4G», оскільки передавання користувацького трафіку 5G NR у цьому випадку реалізується через EPC, канальної структури EPS та відповідні інтерфейси площини користувача [1, с. 18–22; 2, с. 54–61]. В умовах часткових відмов електроживлення найбільше значення мають селективна деградація NR-компоненти, зростання ролі LTE як закріпленого шару, збереження працездатності S1-U/GTP-U та стабільність транспортного середовища для X2- і EPC-зв'язності [1, с. 18–37; 5, с. 1–6; 7, с. 1–3]. Уточнення ролі PDCP, коректне трактування QoS і використання точнішої термінології площини користувача підвищують наукову коректність статті та роблять її ближчою до нормативної термінології 3GPP [1, с. 29–37; 2, с. 54–61].

Література

1. ETSI TS 137 340 V17.3.0 (2023-01). LTE; E-UTRA and NR; Multi-connectivity; Overall description; Stage 2 (3GPP TS 37.340 Release 17). URL: https://cdn.standards.iteh.ai/samples/67922/982c1b9c3dae4dc5999a95564a311f16/ETSI-TS-137-340-V17-3-0-2023-01-.pdf (дата звернення: 27.04.2026).

2. ETSI TS 138 300 V18.3.0 (2024-10). 5G; NR; NR and NG-RAN Overall description; Stage 2 (3GPP TS 38.300 Release 18). URL: https://www.etsi.org/deliver/etsi_ts/138300_138399/138300/18.03.00_60/ts_138300v180300p.pdf (дата звернення: 27.04.2026).

3. ETSI TS 137 340 V15.11.0 (2021-01). LTE; E-UTRA and NR; Multi-connectivity; Overall description; Stage 2 (3GPP TS 37.340 Release 15). URL: https://cdn.standards.iteh.ai/samples/62358/dbd2b8d8ff5846dcba9fb9a630d5332e/ETSI-TS-137-340-V15-11-0-2021-01-.pdf (дата звернення: 27.04.2026).

4. ShareTechnote. Interworking with LTE - NSA / EN-DC in Detail - 5G. URL: https://www.sharetechnote.com/html/5G/5G_LTE_Interworking.html (дата звернення: 27.04.2026).

5. MEF 22.3.1. Transport Services for Mobile Networks. URL: https://www.mplify.net/wp-content/uploads/2020/04/MEF-22-3-1.pdf (дата звернення: 27.04.2026).

6. OpenAirInterface / EURECOM. Demo: OpenAirInterface 5G NSA system with COTS phone. URL: https://www.eurecom.fr/publication/6314/download/comsys-publi-6314.pdf (дата звернення: 27.04.2026).

7. Rusan, A., Vasiu, R. Emulation of backhaul packet loss on the LTE S1-U interface and impact on end user throughput. IEEE ICCP, 2015. Semantic Scholar record: https://www.semanticscholar.org/paper/Emulation-of-backhaul-packet-loss-on-the-LTE-S1-U-Rusan-Vasiu/4892afef0ba664f6a5e1c8a11b5f177bf4edbc89 (дата звернення: 27.04.2026).

8. Power-Consumption Outage in Beyond Fifth Generation Networks. URL: https://pmc.ncbi.nlm.nih.gov/articles/PMC8269066/ (дата звернення: 27.04.2026).

9. Packet Level Resilience for the User Plane in 5G Networks. arXiv. URL: https://arxiv.org/html/2501.17964v2 (дата звернення: 27.04.2026).

10. Resilience of 5G network resilience evaluation mechanism based on Petri Nets. ScienceDirect. URL: https://www.sciencedirect.com/science/article/abs/pii/S1389128624007825 (дата звернення: 27.04.2026).

ОБЪЕДИНЕНИЕ ВСЕГО КОМПЛЕКСА ЗАЩИТ В ВЫКЛЮЧАТЕЛЕ ЗА СЧЕТ ИСПОЛЬЗОВАНИЯ ДЛЯ ЭТОГО ТОЛЬКО ИНФОРМАЦИИ ОТ ДАТЧИКОВ ТОКА

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INTEGRATION OF THE ENTIRE PROTECTION SYSTEM INTO A CIRCUIT BREAKER USING DATA FROM CURRENT SENSORS ONLY

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DOI: 10.5281/zenodo.20457092

ABSTRACT

At present, circuit breakers for low-voltage networks typically employ only overcurrent protection. This is based on the analysis of phase current data obtained from current sensors. More complex protection functions are implemented in separate devices, as the information derived solely from current sensors is insufficient for their design. Therefore, the task of developing a comprehensive protection system based exclusively on information from current sensors is becoming increasingly relevant. To this end, methods for designing a comprehensive protection system have been developed, in which the basis for their design is the same parameters as those used in the design of maximum current protection systems. These parameters are the squares of the discrete values of the phase currents, which are used in current protection schemes to determine the effective values of the currents. It has been established and substantiated that the squares of the discrete current values can also be used to construct the entire protection system. However, for this purpose, it is not the analysis of the variation in the squares of the discrete values of the currents in each phase, as in current protection schemes, that is productive, but rather the variation over time of the sum of these squares of the current values for all three phases. For convenience in the following discussion, the variation over time of this sum of the discrete values of the currents of the three phases is denoted as a force function The rationale for using the force function to design the entire protection system lies in its specific characteristics. Analysis of the force function's behaviour during transient conditions enables protection against currents caused by remote short circuits. Redundancy for feeder circuit-breakers is also provided. Analysis of the nature of the force function in steady-state operation enables protection against neutral wire breaks and the resulting overvoltages.

An algorithm is provided for implementing the entire protection system using information from current sensors only.

Keywords: protection, power grids, power function, algorithm

1. Introduction

At present, the structure of the 0.4 kV network protection system can contain a number of devices in which various types of protection are implemented. But the main protection device, which is necessarily present in all electrical networks, is a circuit breaker. In the trip units of such devices, there are always current protections against overload currents and short-circuit currents (SC), which are formed on the basis of the analysis of information from current sensors. Other protective devices are added in order to increase the reliability of the network protection system. For example, according to the analysis carried out in [1], the function of redundancy of failures of feeder circuit breakers by the input apparatus is available in units BMR3-04 (R&D Center "Mechatronics"). In these units, according to [1], there is also a protection against the break of the neutral wire (N-wire), which is formed on the basis of the analysis of the reverse sequence current. The same protection against the break of the N-wire is available in the MiCOM P126 relay (Schneider Electric). In the above devices, in addition to determining the fact of an N-wire break, there is also protection against the resulting overvoltage. Other devices are also used for surge protection, for example, such as the RN-03-02, [2]. It should be noted that when using all the above and other similar devices, the circuit breaker is used only as an actuator of disconnecting the network when a control signal arrives at it. The use of a circuit breaker tripper for the construction of the entire complex of protections is limited by the fact that the parameters of the protected networks, on the basis of the analysis of which complex protections are built, differ significantly from the parameter, with the help of the analysis of which current protections are built. Thus, in the BMR3-04 units mentioned earlier, analysis of the active and reactive components of the current, as well as the forward-sequence power, is used to implement protection against remote short circuits and to provide redundancy. To implement protection against N-wire open circuits in the devices discussed above, analysis of the reverse-sequence current value is used. It can therefore be concluded that the problem lies in the fact that, when designing complex protection schemes based on the analysis of parameters such as the active and reactive components of the current, power, etc., information from current sensors alone is insufficient,

2. MAIN RESULTS

2.1 Method of implementation of the function of blocking current protections against inrush currents of electric motors.

Protection against remote short-circuit currents and redundancy of failures of feeder devices are based

on the identification of inrush currents of electric motors (ED) and blocking the tripping of the maximum current protection against inrush current. Identification of inrush currents is possible by the value of the power factor cosφ, but it is quite difficult to determine its value by the nature of the change in phase current, since the nature of the change in current in phase depends not only on the value of cosφ, but also from the random moment of the time of the occurrence of the network disturbance current. At present, there is a method for determining the value of cosφ from the analysis of the nature of the change in phase current over time [3]. The technique provides for the determination of the values of constant current components, for which the operator must delineate curves passing in the middle between the current amplitude envelopes on the oscillogram of the transient process of change in time of discrete current values in the phase. It is obviousthat such a method with the involvement of an operator cannot be used in the construction of protections. Therefore, now the method of analyzing the nature of the change in time of discrete values of alternating current in the transient mode to determine the value of cosφ is not used. However, this does not mean that the analysis of discrete values of currents i_j cannot be used in the method for determining the value of cosφ. As the analysis [4] has shown, the value of cosφ can be determined from the dependence on the change in time of the sum of squares of the discrete values of currents of all three phase $F_s\,(t)$:

$$F_s\,(t) = 3I_f^2(1 - 2e^{-t/\tau}\cos\omega\,t + e^{-2t/\tau}) \quad (1),$$

where I_f is the effective value of the phase current, τ is the electromagnetic time constant. As can be seen from expression (1), the nature of the force function does not really depend on the moment of occurrence of the network disturbance current, but depends significantly on the value τ (or $\cos\varphi$).

As can be seen from expression (1), the nature of the force function does not, in fact, depend on the instant at which the network disturbance current arises, but depends significantly on the value of τ (or cosφ). The paper [4] explains why the nature of the power function does not depend on the instant of the network disturbance. That paper presents an analytical study of the reference points of the function F_s(t), the analysis of which enables the design of protection systems for both power networks and electric motors. This article will consider only those final results of the analytical study of the function F_s(t), that are necessary for developing an algorithm for designing the entire complex of power network protection systems.

Figure 1 shows graphs of the force function F_s(t) at different values $\cos\varphi$. The graphs show the reference points of the function F_s(t). The first reference point is the maximum value of the force function($F_{\max}$). The peculiarity of this reference point is that the value F_{max} depends on the value of the shock current of the circuit I_y and this dependence is determined by the following expression:

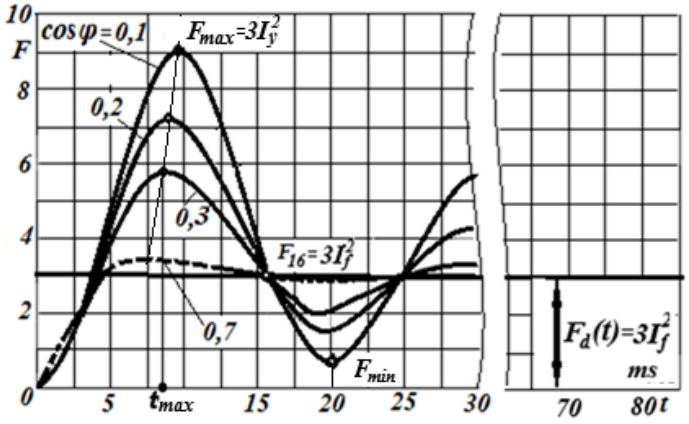

Figure 1 Graphs of the force function at different values of cosφ

$$F_{max} = 3I_y^2 \quad (2)$$

Equation (2) gives the following expression, which makes it possible to determine the magnitude of the shock current of the circuit I_y, if the value F_{max}:

$$I_y = \sqrt{F_{max}/3} \quad (3)$$

The second reference point of the force function is its minimum value F_{min}. The ratio of the maximum value F_{max} and the minimum value F_{min} is a good criterion for estimating the value of $\cos\varphi$.

The third reference point is the value of the force function at the moment of time 16 ms after the occurrence of the network disturbance current – the value F_{16}. As can be seen from the graphs of Fig.1, the value F_{16} at any value $\cos\varphi$ equal, with sufficient accuracy, to the established value of the force function $F_d = 3I_f^2$, where I_f is the effective value of the phase current.

$$I_f = \sqrt{F_{16}/3} \quad (4)$$

Let us consider how the value of the fiducials of the force function can be used to determine the value $\cos\varphi$.

Method 1. The ratio of extreme values of the force function F_{max} and F_{min} essentially depends on the value $\cos\varphi$. Based on the results of the analysis of formula (1), the dependence of the value $\cos\varphi$ on the coefficient of the ratio of extreme values of the force function $K_F = F_{max}/F_{min}$.

Method 2. The value $\cos\varphi$ is determined from the dependence $\cos\varphi = K_F$, which is given in Fig. 2The

value $cos\ \varphi$ can be determined by the coefficient of impact(. Expression for the coefficient $K_y = I_y / I_f$ through the values of reference points F_{max} and F_{16} taking into account expressions (3) and (4), as follows:

$$K_y = \frac{\sqrt{F_{max}}}{\sqrt{F_{16}}} \quad (5)$$

Fig.2 shows the dependence $cos\ \varphi = f(K_y)$

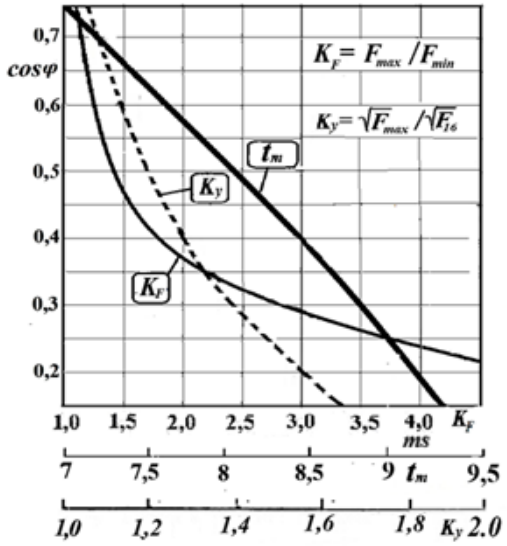

Fig.2 Dependence of the value of the cosφ on the values K_F, t_{max}, K_y

In addition to the two methods discussed for determining the value of cosφ from reference points on the force function, the value of $cos\ \varphi$ can be determined from the time at which the function $F_s(t)$ reaches its maximum value F_{max} – the time t_{max}. Fig.2 shows the dependence $cos\ \varphi = f(t_{max})$.

2.2 Methodology for implementing protection against neutral conductor breaks and the resulting overvoltages

The methodology for protecting against neutral conductor breaks and the resulting overvoltages is based on an analysis of the steady-state behaviour of the power function. Reference [4] states that it is not the force function of the original phase current system $F_s(t)$, that should be analysed, but rather the force function of the reduced current system $F'_s(t)$, in which the phase current values are normalised using normalisation factors.

The analytical expression for the force function $F'_s(t)$ in the event of an N-wire break is as follows:

$$F'_s(t) = \mathbf{3}I_f^2 + \left[I_f^2\ cos\ 2\ \omega t + I_f^2\ cos\ 2\ (\omega t + 2\pi/3) + I_f^2\ cos\ 2\ (\omega t - 2\pi/3)\right] = F'_{sd} + F'_{sa}(t) \quad \mathbf{(7)}$$

where I_f is the effective value of the phase current, F'_{sd} is the constant component of the force function, $F'_{sa}(t)$ is the variable component of the force function.

In the absence of an open circuit in the N-lead of such a reduced current system, the value of the force function remains constant over time:

$$F'_s(t) = F'_{sd} = \mathbf{3}I_f^2 \quad (8)$$

If the N-wire breaks, a variable component F'_{sd} appears in the force function.

Figure 3 shows the graphs of the power function of the reduced current system before and after the break in the N-wire.

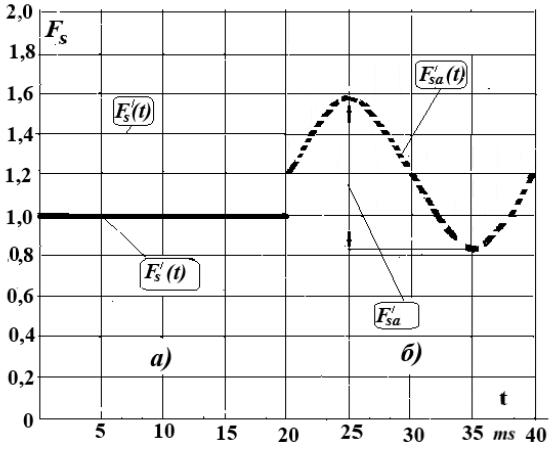

Fig.3 Nature of the power function of the reduced current system before and after the break of the N-wire

The effective value of the component $F'_{sa}(t)$ characterises the magnitude of the overvoltage ΔU_f at the outgoing terminals of the line feed-in circuit breaker. Figure 4 shows the dependence obtained from the results of a laboratory experiment $\Delta U_f = f(F'_{sa})$, where F'_{sa} is the effective value of the variable component of the force function.

2.3 Operating algorithm of the microprocessor-based trip unit when implementing the full range of protection functions

Figure 5 shows the operating algorithm of the trip unit when implementing the full range of protection functions based solely on information from current sensors. The blocks shown in the algorithm do not physically exist; they represent a set of mathematical and logical operations.

1. Module 1 receives information from the current sensors regarding the current values in phases a, b and c. The discrete values of the phase currents a, b and c ic are stored in the microprocessor's memory over a time interval equal to one current cycle (20 ms at a frequency of 50 Hz). The time-dependent relationships of the current values – $i_a(t)$, $i_b(t)$ and $i_c(t)$– are stored in the microprocessor's memory. These relationships are subsequently used to determine the network disturbance current.

2. In Module 2, the discrete values of the network disturbance currents are determined as the difference between the discrete current values of the current period and those of the previous period; these values are denoted as $i_{\sigma a}$, $i_{\sigma b}$ and $i_{\sigma c}$. If these values are smaller than the current measurement errors, no further operations are performed. Otherwise, in the same module, the squares of the discrete disturbance current values $i^2_{\sigma a}$ $i^2_{\sigma b}$ and $i^2_{\sigma c}$are determined.

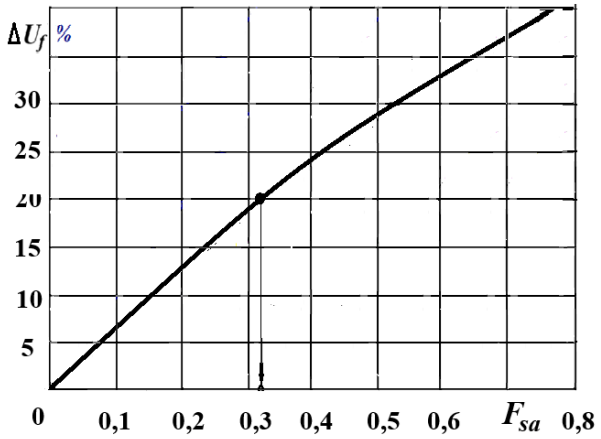

Fig.4 Dependence of the value of overvoltage ΔU_f on the value of F_{sa}

3. In module 3, the effective values of the disturbance current in phases I_a , I_b and I_c _ are determined.

4. In module 4, the current value in each phase is compared with the short-circuit current setting I_{sc}; if I_$I_a \geq I_{sc}$, or $I_b \geq I_{sc}$ or $I_c \geq I_{sc}$, 'Yes' control signal is generated and sent to the actuator (IE) – to module 5.

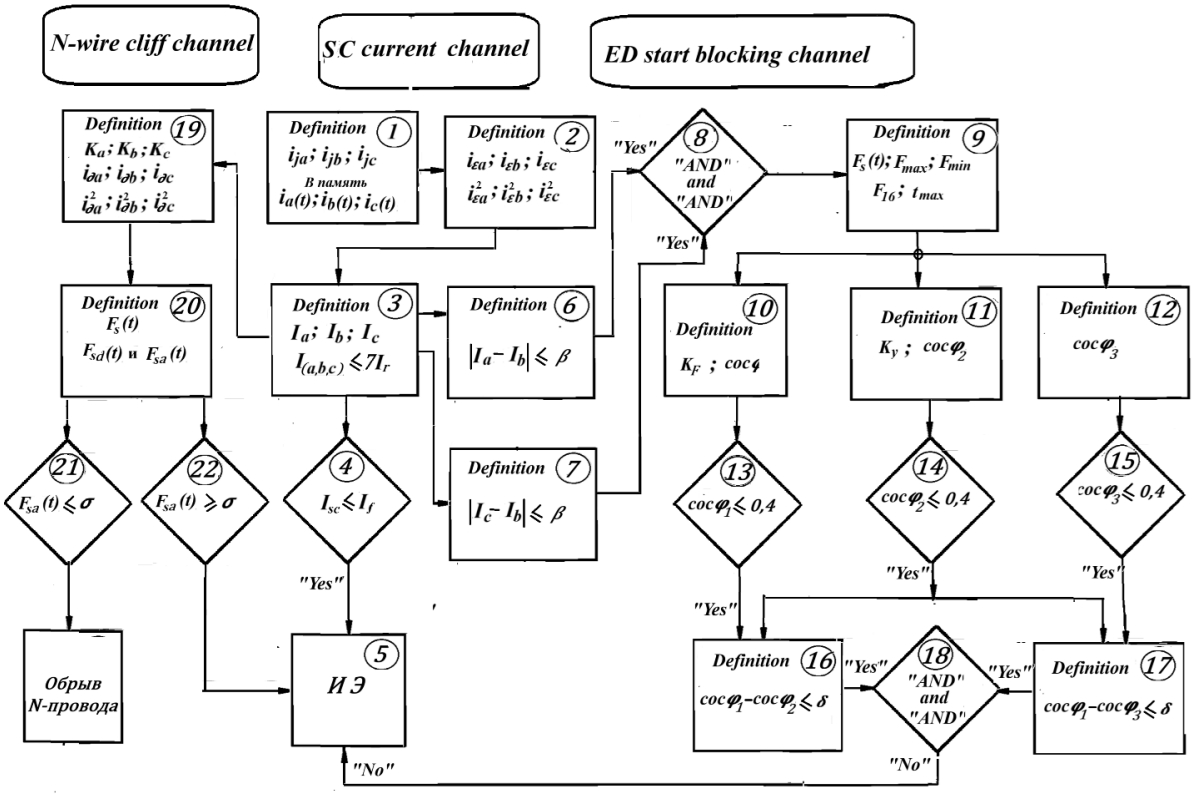

Fig.5 Algorithm for the implementation of the entire complex of protections

5. In module 5, upon receipt of the 'Yes' signal, the protection trip time is set to ensure selective operation with downstream feeder equipment.

6. In module 6, the values of phase a current a (I_a) and phase a current b (I_b) are compared. If the absolute value of the difference between these currents is less than the error in determining the effective values of the phase currents β, the currents in question are considered to be equal and a 'Yes' control signal is generated.

7. In module 7, the values of phase c current c (I_c) and phase b current b (I_b) are compared. If the absolute value of the difference between the specified currents is less than the error in determining the effective values of the phase currents, β, the currents in question are considered to be identical and a 'Yes' control signal is generated.

8. In module 8, upon receiving two 'Yes' signals from blocks 6 and 7, a control signal is generated to block 9 for the purpose of performing calculations.

9. In module 9, the force function of the network with identical phase currents F_s(t), is determined; the reference points of the force function—F_{max}, F_{min} , F_{16} and the time t_{max} .

10. In module 10, the coefficient $K_F = F_{max}/F_{min}$ is determined, after which the value of cosφ₁ is determined from the relationship $cos\varphi=f(K_F)$.

11. In module 11, the impact coefficient $K_y = F_{max}/F_{16}$ is determined, and the value of $cos\varphi_2$ is determined from the relationship $cos\varphi=f(K_y)$.

12. In module 12, the value of $cos\varphi_3$is determined from the relationship $cos\varphi=f(t_{max})$.

13. In module 13, the value of $cos\varphi_1$ is compared with 0.4, and if cosφ$_1 \leq$ 0,4, a 'Yes' signal is generated.

14. In module 14, the value of $cos\varphi_2$is compared with 0.4, and if $cos\varphi_2 \leq$ 0,4, a 'Yes' signal is generated.

15. In module 15, the value of $cos\varphi_3$is compared with 0.4, and if cosφ_3 ≤ $cos\varphi_3 \leq$ 0,4' signal is generated.

16. In module 16, the difference between the values of cosφ₁ and cosφ₂ is calculated; if the absolute value of I$cos\varphi_1$-$cos\varphi_2$I is less than the current measurement error σ I$cos\varphi_1$-$cos\varphi_2$I≤ σ, a 'Yes' signal is generated.

17. In module 17, the difference between the values of $cos\varphi_3$ and $cos\varphi_2$ is determined, if the absolute value of величина I$cos\varphi_3$-$cos\varphi_2$I is less than the current measurement error σ (i.e. величина I$cos\varphi_3$-$cos\varphi_2$I ≤ σ), a 'Yes' signal is generated.

18. In module 18, upon receiving two 'Yes' signals, a 'No' signal is generated, which is fed to module 5 and blocks the actuation of the actuator IE.

19. In Module 19, the balancing coefficients for the phase currents are determined, for example, if $K_a = I_a/I_b$, then $K_a = 1$ и $K_c = I_c/I_b$. In the same module, the discrete values of the phase currents are determined taking into account the balancing coefficients – the values - $i_{\partial a}$, $i_{\partial b}$, $i_{\partial c}$and the squares of these discrete currents $i^2_{\partial a}$, $i^2_{\partial b}$, $i^2_{\partial c}$.

20 In Module 20, the force function $F_s\,(t)$ is determined and checked for the presence of its components – the constant $F_{sd}\,(t)$ and the variable $F_{sa}\,(t)$.

21. In module 21, if there is a variable component $F_{sa}\,(t)$, its value is compared with the permissible value σ, which characterises the overvoltage ΔU_f exceeding the permissible value σ. If $F_{sa}\,(t) \leq \sigma$, an information signal 'N-wire break' is generated.

22. In module 22, the value of the variable component $F_{sa}(t)$ is compared with the permissible value σ, which characterises the magnitude of the overvoltage ΔU_f exceeding the permissible value σ. If $F_{sa}(t) \geq \sigma$, a control signal is generated to the actuator IE to activate the protection.

3. SUMMARY

The objective of developing methods for designing the entire protection system for 0.4 kV electrical networks based solely on the analysis of data from current sensors was set and achieved. The methods developed are based on the analysis of the force function, which represents the time-dependent variation of the sum of the squares of the discrete phase currents. Whilst the time-dependent variation of the squares of the phase currents is used when designing maximum current protection, the time-dependent variation of the sum of the squares of the currents of all three phases is used to design more complex protection schemes. The use of the force function for designing complex protection schemes is due to the characteristics of the power function in both transient and steady-state conditions.

Analysis of the nature of the force function during transient conditions makes it possible to quickly determine, within 16 ms of the occurrence of a fault current, both the effective value of the fault current and the power factor of the electrical circuit. This enables the reliable identification of electric motor starting currents and prevents the protection from tripping. This enables protection against remote short-circuit currents and the provision of backup by input devices in the event of feeder device failures.

Analysis of the nature of the force function in steady-state operation allows the design of protection against neutral wire breaks and the resulting overvoltages.

The algorithm for implementing the entire set of protection functions in a microprocessor-based circuit breaker release is presented. Compared to the algorithm for implementing current protection, the comprehensive algorithm is significantly more complex and requires a higher cost for the microprocessor-based system. However, using a single, more expensive circuit-breaker with a comprehensive protection system will be more cost-effective than using several devices in the network protection system.

References

1. A. M. Ershov, A. V. Khlopova, A. I. Sidorov. "Neutral Wire Break Monitoring Device in 0.38 kV Networks," Power Tehnology and Enginttring, September 5, 2020, pp. 434-437

2. Electronic protection relays LR97D and LT47, SchneiderElectric. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwjp276BkdH8AhVyAhAIHWs1A-EQFnoEA0QAQ&url=https%3A%2F%2Fwww.electrocentr.com.ua%2Fru%2Fproducts%2Fmotorcontrol%2Fprotectionrelays%2Flr97_lt47.html&usg=AOvVaw3CL-gWt2ARMuVdJ9XliA-v

3. V.E. Rainin, A.S. Kobozev, Yu.N. Barchenkov "Methods for Determining the Parameters of the Test Circuit for the Automated Process of Testing Electrical Apparatuses", Elektrotechnica, 2016, No 7, pp. 58-62

4. *Kobozev Alexander, "* Force as an effective tool for protecting electrical networks and electric motors of buildings", German International Journal of Modern Science, No 124, 2026, pp. 78-83

МЕТОД ПЕРЕВІРКИ ЗГЕНЕРОВАНОГО ПРОГРАМНОГО КОДУ У ЗАХИЩЕНОМУ СЕРЕДОВИЩІ WEBASSEMBLY ІЗ ЗАСТОСУВАННЯМ БАГАТОРІВНЕВОГО АНАЛІЗУ ТА МОДЕЛЕЙ ШТУЧНОГО ІНТЕЛЕКТУ

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A MULTI-TIER VERIFICATION METHOD FOR LLM-GENERATED CODE IN SANDBOXED WEBASSEMBLY ENVIRONMENTS WITH AI-AUGMENTED ANALYSIS

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DOI: 10.5281/zenodo.20457104

АНОТАЦІЯ

Запропоновано метод перевірки програмного коду, згенерованого великими мовними моделями, що поєднує: (i) компіляцію кожного кандидатного модуля у формат wasm32-unknown-unknown WebAssembly з явно визначеним набором хост-імпортів на основі capability-моделі безпеки; (ii) багаторівневий статичний аналіз над абстрактним синтаксичним деревом, графом потоків керування, графом потоків даних та проміжним представленням Wasm; (iii) семантичний аналіз із застосуванням моделей штучного інтелекту – трансформерного енкодера для перевірки відповідності наміру, графової нейронної мережі з механізмом уваги над уніфікованим графом CFG/DFG та детектора аномалій типу Isolation Forest над шляхами виконання; (iv) детерміноване динамічне виконання у пісочниці на основі Wasmtime з обмеженням обчислювальних ресурсів (fuel metering), переривань за епохами та хост-імпортами, обмеженими capability-політикою. Метод реалізує політики безпеки та архітектурні політики бізнес-системи на рівні окремого модуля і формує структурований вердикт, який замикає зворотний зв'язок з генератором коду до моменту виконання функціональних і безпекових вимог. Експериментальна оцінка на синтетичному корпусі з 12 800 модулів демонструє приріст метрики F1 з 0,58 (правила статичного аналізу) до 0,95 (агрегований вердикт).

ABSTRACT

A verification method is proposed for source artefacts produced by large language models. The method combines: (i) compilation of every candidate module to the wasm32-unknown-unknown WebAssembly target with an explicit host-supplied capability set; (ii) a multi-tier static analysis pipeline operating over the abstract syntax tree, control-flow graph, data-flow graph and Wasm intermediate representation; (iii) AI-augmented semantic analysis based on a transformer encoder for intent matching, a graph attention network over the unified control/data-flow graph, and an isolation-forest anomaly detector over runtime execution traces; and (iv) deterministic dynamic execution inside a Wasmtime sandbox with fuel metering, epoch-based interruption and capability-restricted host imports. The method enforces architectural and security policies of the host business system on a per-module basis and provides a structured verdict that drives a closed feedback loop back into the generator until the module satisfies both functional and security requirements. Empirical evaluation on a synthetic corpus of 12,800 modules shows that the aggregated verdict reaches F1 = 0.95, compared with 0.58 for static rules alone.

Ключові слова: WebAssembly, ізоляція, перевірка коду, великі мовні моделі, згенерований код, графові нейронні мережі, трансформери, виявлення аномалій, capability-безпека, ланцюг постачання програмного забезпечення.

Keywords: WebAssembly, sandboxing, code verification, large language models, generated code, graph neural networks, transformers, anomaly detection, capability security, software supply chain.

Problem statement.

Code-generating language models are now embedded in production developer workflows, build pipelines, and increasingly in *runtime* systems where natural-language specifications are compiled, at request time, into executable artefacts. This shift transforms code generation from a developer-assistance feature into a software supply-chain component whose output must satisfy two simultaneous constraints: functional correctness with respect to the developer's intent, and conformance to the security and architectural policies of the deploying system. Empirical studies have shown that machine-generated code, even when functionally correct on benchmark tasks, exhibits non-trivial rates of insecure patterns [4, p. 5], [5, p. 3]. Beyond classic memory- and injection-class defects, generated code can introduce subtler hazards: dependency confusion via fabricated package names, opaque network or filesystem side-effects, control-flow obfuscation that bypasses naive linters, and prompt-induced inclusion of attacker-controlled snippets.

Conventional defenses — static linters, signature-based scanners and ad-hoc sandboxes — are individually insufficient. Linters miss semantic intent mismatch; signature scanners miss novel constructions; coarse sandboxes either over-permit (for example, default WASI access) or under-permit (blocking legiti-

mate computation). The problem we address is therefore the construction of a verification regime adequate to *runtime-generated* code, which must be (a) language-agnostic, since LLMs may emit Rust, C, Go, TypeScript or AssemblyScript indifferently; (b) fine-grained, capable of evaluating thousands of small modules per business system; (c) defense-in-depth, layering static, dynamic and learning-based analysis; and (d) closed-loop, returning structured verdicts to the generator.

Analysis of recent research and publications.

WebAssembly's structured control flow, linear memory and absence of ambient authority make it a strong starting point for sandboxing untrusted code [1, p. 192]. The wasm32-unknown-unknown target — as distinct from wasm32-wasi — exposes no system calls; every external effect must be explicitly imported. Recent work has nevertheless shown that the Wasm memory model permits its own class of intra-sandbox attacks [2, p. 217], which motivates the additional analysis layers we describe.

Symbolic and abstract-interpretation tooling for Wasm has matured, and graph-based vulnerability detectors over control- and data-flow representations of source code, of which Devign [8, p. 10198] is canonical, demonstrate that learned representations can outperform hand-engineered rule sets. Pretrained transformer encoders such as CodeBERT [6, p. 1538] and GraphCodeBERT [7, p. 4] provide cross-modal embeddings that align natural-language specifications with source code; we adopt them as a scoring mechanism rather than a generation mechanism. The capability-security tradition [10, p. 22] grounds our import-restricted host: a module possesses no authority it has not been explicitly granted, and the component model of WebAssembly makes such authorization composable. Recent surveys of WebAssembly security emphasize that sandboxing must be combined with runtime, memory and host-interface controls rather than treated as a complete defense by itself [13]. Recent empirical work on LLM-generated programs also confirms that generated code may remain insecure unless the generation process is constrained by explicit security guidance and verification feedback [14]. For unsupervised characterization of execution traces we adopt the isolation-forest detector [11, p. 413] owing to its low time complexity and small training-set requirements.

Identification of previously unresolved parts of the general problem.

The cited tools target human-authored code and pre-deployment review pipelines. Three gaps remain. First, no single approach addresses *runtime* code synthesis where modules are produced, verified and deployed within a single request cycle. Second, language-agnostic verification across the heterogeneous set of source languages an LLM may emit is rarely treated; existing tools tend to be source-language-specific. Third, the feedback signal returned to the generator is typically binary (admit/reject), which wastes generation work and offers no constructive guidance.

We further observe that the adversary in this setting is not necessarily malicious in the classical sense: it is a generator whose output distribution is shaped by training data, prompt content and retrieved context, and which may therefore emit code that is unintentionally — or, in the case of prompt-injected context, intentionally — harmful. The generator is treated as untrusted. The host runtime, the analysis pipeline and the host-side imports are treated as trusted. The adversarial goals are: (G1) escape from the Wasm sandbox; (G2) abuse of host imports beyond developer intent; (G3) covert resource exhaustion; (G4) data exfiltration via permitted channels but in unintended quantity or shape; and (G5) production of functionally plausible code whose hidden behavior contradicts the natural-language specification.

Purpose of the article.

The purpose of the article is to propose, formally describe and experimentally validate a method for verifying LLM-generated source code in a sandboxed WebAssembly environment which combines multi-tier static and dynamic analysis with adaptive artificial-intelligence models, enforces the security and architectural policies of the host business system on each generated module, automatically detects potentially dangerous constructs, hidden invocations and attempts to evade security policies, and returns structured feedback to the generator. The method must remain language-agnostic at the source level, support fine-grained deployment of thousands of small modules per system, and admit a verification latency budget compatible with interactive regeneration.

Presentation of the main research material.

Method overview. Let S denote a natural-language specification, L a set of permitted source languages, P a set of host-defined security and architectural policies, and I the set of host-supplied import functions exposed to candidate modules. The generator G produces a candidate source artefact $c \in L$ from S. The verification function is defined as

$$V : (c, S, P, I) \rightarrow \{ ADMIT, REJECT, REGENERATE(\Delta) \}, (1)$$

where Δ is a structured feedback packet returned to G. The method realizes V as a six-stage pipeline: (1) specification normalization; (2) compilation to Wasm; (3) static analysis; (4) AI-augmented semantic analysis; (5) dynamic analysis in the sandbox; (6) verdict aggregation. If any stage produces a hard failure, the pipeline short-circuits either to REJECT (irrecoverable) or to REGENERATE (recoverable) with Δ describing the failure category, location and a constraint hint.

Specification normalization and capability binding. The specification S is parsed into a typed contract $\hat{S}$ = (signature, pre, post, caps), in which signature fixes the exported function, pre and post fix the contract pre- and post-conditions extractable from S, and caps enumerate the exact host imports the module is permitted to declare. Because wasm32-unknown-unknown provides no implicit imports, the import section of a compiled module is fully visible; any attempt to smuggle a system call fails at link time, before any code executes. An example contract for a string-transform module is:

```
    signature: "transform_record(ptr:
u32, len: u32) -> u32"
    caps:
     - host_log_debug(ptr: u32, len:
u32)
```

```
    - host_allocate(size: u32) -> u32
  postconditions:
    - output_is_valid_utf8: true
    - max_allocations_per_call: 4
    - max_fuel_per_call: 1_000_000
```

Compilation pipeline.

Rust sources are compiled with rustc --target=wasm32-unknown-unknown -C opt-level=z -C lto=fat; C and C++ with clang --target=wasm32 -nostdlib; Go with TinyGo on the equivalent target; TypeScript with AssemblyScript. No source language is permitted to link against libc or any system runtime. A post-compilation passes with wasm-tools validate rejects malformed binaries; the producer's section is stripped to reduce side-channel signal. Typical module size for the workloads considered in Section 5 is 1–4 KiB.

Static analysis. At the source level the AST is parsed with tree-sitter and screened for unsafe blocks (Rust), inline assembly, raw pointer arithmetic not covered by the contract, and reflective constructs in higher-level languages. At the Wasm IR level, walrus is used to build a control-flow graph per function and a data-flow graph over locals, globals and the linear memory abstracted into typed regions. Rule patterns include: declared imports versus permitted imports (must be a subset of $\hat{S}$.caps); indirect calls whose call_indirect tables cannot be statically bounded; memory.grow invocations not justified by the contract; unreachable code with observable side-effects; and the export surface, which must be a subset of {$\hat{S}$.signature}. Formally, with import set imp(M) and export set exp(M):

$$StaticOK(M, \hat{S}) \Leftrightarrow imp(M) \subseteq \hat{S}.caps \wedge exp(M) \subseteq \{\hat{S}.signature\}. \quad (2)$$

Condition (2) is necessary but not sufficient for admission; semantic and behavioral checks follow.

AI-augmented semantic analysis. Three learned components are added on top of the static tier. A pre-trained GraphCodeBERT encoder E embeds both S and a serialized form of the function body, producing vectors e_s, $e_c \in \mathbb{R}^d$. A learned bilinear projection W yields an intent score

$$s\_intent(c, S) = \sigma(e_s^T W e_c). \quad (3)$$

Low values of s_intent flag semantic drift, that is, code whose token-level behavior does not align with the natural-language specification. A two-layer graph attention network (GATv2) over the unified CFG/DFG graph G_M = (V, E, X) produces a per-graph embedding and a classifier head outputs an unsafe-class probability $s\_gnn(M) \in [0, 1]$. Vertices are basic blocks annotated with opcode histograms, local-type signatures and memory-touch flags; edges carry control-flow or data-flow labels. Sandboxed execution (see below) emits a trace τ of host-import invocations, memory-region access counts, fuel consumption and branch-frequency vectors; an isolation forest trained on traces of contract-conformant modules produces an anomaly score $s\_anom(\tau)$.

Dynamic analysis in the sandbox. Each candidate M that survives the static and semantic tiers is executed inside a Wasmtime Engine, whose security model is documented in [15], configured with consume_fuel(true) and the per-call budget from $\hat{S}$; epoch_interruption(true) to bound wall-clock time independently of fuel; a linear-memory hard cap (typically 64 MiB) enforced via MemoryType and ResourceLimiter; and all imports supplied as instrumented host shims that record every invocation and enforce per-import quotas. Inputs are drawn from contract examples, contract-derived property-based fuzzing, and a regression set. Per-input outcomes (return value, trap or success, fuel consumed, trace τ) are aggregated into per-module metrics. The structural advantage of wasm32-unknown-unknown over wasm32-wasi for this use case is decisive: every externally observable effect of M is visible to the host because there is no system call to monitor at the kernel level — there is no system call at all. The module can invoke only the functions the host has handed it.

Verdict aggregation. Given normalized scores s_intent, s_gnn, s_anom and the static boolean b_static, the verdict is:

$$V(c) = REJECT \text{ if } \neg b\_static \text{ or any hard policy fails;}$$
$$V(c) = ADMIT \text{ if } s\_intent \geq \theta_1 \wedge s\_gnn \leq \theta_2 \wedge s\_anom \leq \theta_3;$$
$$V(c) = REGENERATE(\Delta) \text{ otherwise, } (4)$$

with thresholds θ_i calibrated on a held-out validation set. The feedback packet Δ encodes the failing layer, the offending construct (for example, basic-block identifiers and the imports they dominate) and a constraint hint to the generator (for example, do not call host_allocate more than four times per invocation). The closed-loop nature of the system is key: in our experiments the median LLM-generated module is admitted within two to three regeneration rounds.

Reference implementation. The method is implemented in Rust (host runtime and analysis core) and Python (ML services) connected by a gRPC contract, with Wasmtime 18.x as the sandbox runtime. The kernel of the host runtime loads a candidate module, validates its imports against the contract, wires a fixed set of capability imports, and runs the exported entry point under fuel and epoch limits:

```
    // crates/wasm-sandbox/src/runner.rs
    use anyhow::{anyhow, Result};
    use wasmtime::*;

    pub struct Capabilities {
        pub max_fuel: u64,
        pub epoch_deadline_ms: u64,
        pub max_memory_pages: u32,
        pub   allowed_imports:   &'static
[&'static str],
    }

    pub fn run_module(wasm: &[u8], caps:
Capabilities) -> Result<Vec<TraceEvent>>
{
      let mut config = Config::new();
      config.consume_fuel(true);
      config.epoch_interruption(true);
      config.wasm_simd(false);
      let engine = Engine::new(&config)?;

      //    Validate    imports    BEFORE
instantiation.
```

```
      for payload in wasmparser::Parser::new(0).parse_all(wasm) {
        if let wasmparser::Payload::ImportSection(reader) = payload? {
          for imp in reader {
            let imp = imp?;
            let key = format!("{}::{}", imp.module, imp.name);
            if !caps.allowed_imports.iter().any(|a| *a == key) {
              return Err(anyhow!("disallowed import: {}", key));
            }
          }
        }
      }

       let module = Module::new(&engine, wasm)?;
      let mut store = Store::new(&engine, HostState::new(caps));

      store.set_fuel(store.data().caps.max_fuel)?;
      store.set_epoch_deadline(1);

      let mut linker = Linker::new(&engine);
      linker.func_wrap("env", "host_log_debug",
        |mut c: Caller<'_, HostState>, ptr: u32, len: u32| -> Result<(), Trap> {
          c.data_mut().record("host_log_debug", &[ptr as u64, len as u64]);
          Ok(())
        })?;
      linker.func_wrap("env", "host_allocate",
        |mut c: Caller<'_, HostState>, size: u32| -> Result<u32, Trap> {
          let s = c.data_mut();
          if s.alloc_count >= 4 { return Err(Trap::new("alloc quota")); }
          s.alloc_count += 1;
          Ok(call_guest_alloc(&mut c, size)?)
        })?;

      let inst = linker.instantiate(&mut store, &module)?;
      let f = inst.get_typed_func::<(u32, u32), u32>(&mut store, "transform_record")?;
      let _ = f.call(&mut store, (0, 0))?;
      Ok(store.into_data().trace)
    }
```

A representative module that the generator might produce for the contract shown above is the following Rust source, compiled to wasm32-unknown-unknown and producing a binary of approximately 1–4 KiB:

```
    // crates/example-guest/src/lib.rs
    #![no_std]
    #![no_main]

    extern "C" {
      fn host_log_debug(ptr: *const u8, len: u32);
      fn host_allocate(size: u32) -> *mut u8;
    }

    #[panic_handler]
    fn panic(_: &core::panic::PanicInfo) -> ! { loop {} }

    #[no_mangle]
    pub extern "C" fn transform_record(ptr: *const u8, len: u32) -> u32 {
      let out = unsafe { host_allocate(len) };
      if out.is_null() { return 0; }
      for i in 0..len {
        let b = unsafe { *ptr.add(i as usize) };
        let up = if b >= b'a' && b <= b'z' { b - 32 } else { b };
        unsafe { *out.add(i as usize) = up; }
      }
      let tag = b"transformed";
      unsafe { host_log_debug(tag.as_ptr(), tag.len() as u32); }
      out as u32
    }
```

Control- and data-flow extraction over the resulting Wasm IR is performed with walrus; the resulting graph is shipped to the Python analysis service in a flat tensor representation. The GAT classifier is implemented in PyTorch Geometric:

```
    # services/ml/gat_classifier.py
    import torch, torch.nn as nn, torch.nn.functional as F
    from torch_geometric.nn import GATv2Conv, global_mean_pool

    class WasmGAT(nn.Module):
      def __init__(self, in_dim=258, hidden=64, heads=4):
        super().__init__()
        self.g1 = GATv2Conv(in_dim, hidden, heads=heads, edge_dim=4)
        self.g2 = GATv2Conv(hidden * heads, hidden, heads=1, edge_dim=4)
        self.head = nn.Sequential(
          nn.Linear(hidden, hidden), nn.ReLU(), nn.Dropout(0.2),
          nn.Linear(hidden, 1),
        )
      def forward(self, x, edge_index, edge_attr, batch):
        h = F.elu(self.g1(x, edge_index, edge_attr))
        h = F.elu(self.g2(h, edge_index, edge_attr))
        return torch.sigmoid(self.head(global_mean_pool(h, batch))).squeeze(-1)
```

Experimental evaluation. A synthetic corpus of 12,800 Wasm modules was assembled across four families of tasks (string transform, record validation, structured-log redaction, numeric reducer). The corpus was generated in controlled batches from fixed task tem-

plates and then normalized through the same compilation pipeline used by the proposed verifier. Half of the modules were conformant: generated, manually reviewed and contract-passing. The other half were perturbed by ten injection strategies (extra host-import calls, unreachable side-effects, indirect-call laundering, fuel-exhaustion loops, memory-grow spam, spec-mismatched output fields, and others), each applied to a random subset and re-compiled. To reduce leakage between training and testing, modules derived from the same task template and perturbation seed were kept in the same split. The GAT was trained on 9,000 modules with stratified sampling, validated on 1,600 and tested on 2,200. Thresholds theta_1, theta_2 and theta_3 were selected only on the validation split and then fixed for the final test run. Per-layer detection performance on the test set is summarised in Table 1.

Table 1

Per-layer detection performance (test set)

Analysis layer	**Precision**	**Recall**	**F1**
Static rules	0.99	0.41	0.58
GAT on CFG/DFG	0.92	0.83	0.87
Transformer intent	0.88	0.79	0.83
Trace anomaly (IF)	0.81	0.85	0.83
Aggregated verdict V	0.97	0.94	0.95

Across 1,000 regeneration episodes the median module reached ADMIT in two rounds (mean 2.7); 4.3 % of episodes required more than five rounds and 1.1 % terminated in REJECT. The static tier alone admitted 71 % of unsafe modules: its precision on the constructs it can detect is near-perfect, but its recall is low because most semantic and behavioral hazards are invisible to it. The full pipeline reduced the unsafe admission rate to 0.6 %.

End-to-end per-module verification latency was measured on a single eight-core workstation; results are summarized in Table 2.

Table 2

Verification latency per module

Stage	**Median (ms)**	**p99 (ms)**
Compile and strip	180	430
Static analysis	9	24
GAT scoring	12	31
Intent scoring	48	110
Dynamic execution and trace	85	310
Aggregation and verdict	1	3
Total	335	830

A sub-second budget per module is consistent with thousand-module business systems that re-verify on policy change overnight, and well within interactive use during the regeneration loop.

Conclusions and proposals.

A method has been proposed for verifying source artefacts produced by large language models, grounded in three principles: explicit capability binding via compilation to the wasm32-unknown-unknown target, layered static and dynamic analysis over the WebAssembly intermediate representation, and adaptive AI components — transformer-based intent matching, graph attention over the unified control- and data-flow graph, and isolation-forest anomaly detection over execution traces — combined into an aggregated verdict that closes a feedback loop back into the generator. The method enforces the security and architectural policies of the host business system on every generated module, automatically detects potentially dangerous constructs, hidden invocations and attempts to evade security policies, and yields a deployable artefact of small size, language-agnostic provenance and strong isolation. Empirical results show an aggregated F1 of 0.95 against 0.58 for static rules alone, with sub-second per-module verification latency.

The principal limitation is the dependence of the learned components on the training corpus: novel exploitation strategies will require periodic retraining of the graph and anomaly models. Intent matching depends on a clean natural-language specification; degenerate or contradictory specifications degrade the signal. The present evaluation uses a synthetic corpus, so the reported F1 values should be interpreted as controlled experimental evidence rather than a final estimate for all production workloads. Side-channel attacks (timing,

cache) are out of scope and require orthogonal mitigations such as constant-time enforcement. Future work will extend the method to the WebAssembly component model for richer typed interfaces, integrate differential testing across compiler back-ends, publish an anonymized benchmark corpus, and investigate formal verification of the host-import shims as a trusted computing base of minimal size.

References

1. Haas A., Rossberg A., Schuff D. L., Titzer B. L., Holman M., Gohman D., Wagner L., Zakai A., Bastien J. F. Bringing the Web up to Speed with WebAssembly // Proceedings of the 38th ACM SIGPLAN Conference on Programming Language Design and Implementation (PLDI). — ACM, 2017. — P. 185–200.

2. Lehmann D., Kinder J., Pradel M. Everything Old is New Again: Binary Security of WebAssembly // Proceedings of the 29th USENIX Security Symposium. — USENIX, 2020. — P. 217–234.

3. Watt C. Mechanising and Verifying the WebAssembly Specification // Proceedings of the 7th ACM SIGPLAN International Conference on Certified Programs and Proofs (CPP). — ACM, 2018. — P. 53–65.

4. Pearce H., Ahmad B., Tan B., Dolan-Gavitt B., Karri R. Asleep at the Keyboard? Assessing the Security of GitHub Copilot's Code Contributions // 43rd IEEE Symposium on Security and Privacy (S&P). — IEEE, 2022. — P. 754–768.

5. Asare O., Nagappan M., Asokan N. Is GitHub's Copilot as Bad as Humans at Introducing Vulnerabilities in Code? // Empirical Software Engineering. — 2023. — Vol. 28, No. 6. — P. 1–24.

6. Feng Z., Guo D., Tang D., Duan N., Feng X., Gong M., Shou L., Qin B., Liu T., Jiang D., Zhou M. CodeBERT: A Pre-Trained Model for Programming and Natural Languages // Findings of EMNLP 2020. — ACL, 2020. — P. 1536–1547.

7. Guo D., Ren S., Lu S., Feng Z., Tang D., Liu S., Zhou L., Duan N., Svyatkovskiy A., Fu S., Tufano M., Deng S. K., Clement C., Drain D., Sundaresan N., Yin J., Jiang D., Zhou M. GraphCodeBERT: Pre-training Code Representations with Data Flow // Proceedings of the International Conference on Learning Representations (ICLR). — 2021. — P. 1–18.

8. Zhou Y., Liu S., Siow J., Du X., Liu Y. Devign: Effective Vulnerability Identification by Learning Comprehensive Program Semantics via Graph Neural Networks // Advances in Neural Information Processing Systems (NeurIPS). — 2019. — Vol. 32. — P. 10197–10207.

9. Veličković P., Cucurull G., Casanova A., Romero A., Liò P., Bengio Y. Graph Attention Networks // Proceedings of the International Conference on Learning Representations (ICLR). — 2018. — P. 1–12.

10. Miller M. S. Robust Composition: Towards a Unified Approach to Access Control and Concurrency Control: PhD thesis. — Johns Hopkins University, Baltimore, 2006. — 302 p.

11. Liu F. T., Ting K. M., Zhou Z.-H. Isolation Forest // Proceedings of the Eighth IEEE International Conference on Data Mining (ICDM). — IEEE, 2008. — P. 413–422.

12. Bytecode Alliance. Wasmtime: A Standalone Runtime for WebAssembly [Electronic resource]. — Mode of access: https://wasmtime.dev (accessed 14 May 2026).

13. Perrone G., Romano S. WebAssembly and Security: a review // arXiv:2407.12297. - 2024. - DOI: 10.48550/arXiv.2407.12297.

14. Goetz S., Schaad A. You still have to study: On the Security of LLM generated code // arXiv:2408.07106. - 2024. - DOI: 10.48550/arXiv.2408.07106.

15. Bytecode Alliance. Security - Wasmtime [Electronic resource]. - Mode of access: https://docs.wasmtime.dev/security.html (accessed 14 May 2026).

No 189 (2026)

Sciences of Europe
(Praha, Czech Republic)

ISSN 3162-2364
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Journal is published in Czech, English, Polish, Russian, Chinese, German and French, Ukrainian.
Articles are accepted each month.
Frequency: 24 issues per year.
Format - A4
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